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INTEGRATING POWER-FLOW, RESILIENCE, AND COST MODELS FOR NAVAL INSTALLATION MICROGRID

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SYSTEMS ENGINEERING CAPSTONE REPORT

INTEGRATING POWER-FLOW, RESILIENCE, AND COST MODELS FOR NAVAL INSTALLATION MICROGRIDS

by

Curtis D. Bolen, Victoria Chu, Andy Q. Dang, Paul T. Kim, Christian Proctor, and Bridget R. Shideler

March 2021

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Existing military microgrid analysis tools lack an integrated system analysis process to fully assess energy resilience and microgrid cost. This capstone describes the development of a common streamlined tool and methodology to improve the ability to assess energy resilience for military microgrids using event scenarios including deliberate attacks and natural disasters. The resilience metric used in this report, defined as the expected lifecycle mission impact (ELMI), quantifies microgrid resilience in terms of the microgrid's ability to minimize mission impact against all potential threats to power disruption. The tool considers a realistic set of scenarios that could disrupt power allowing users to compare distributed energy resource (DER) changes against a single microgrid architecture to determine the best balance between cost and resilience. Users can configure the tool to allow for change in microgrid load or updates to equipment costs. A supplemental user's guide provides a thorough walkthrough of the tool, and a supplemental case study demonstrates the tool functionality by analyzing an existing naval installation microgrid.

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ABSTRACT

Existing military microgrid analysis tools lack an integrated system analysis process to fully assess energy resilience and microgrid cost. This capstone describes the development of a common streamlined tool and methodology to improve the ability to assess energy resilience for military microgrids using event scenarios including deliberate attacks and natural disasters. The resilience metric used in this report, defined as the expected lifecycle mission impact (ELMI), quantifies microgrid resilience in terms of the microgrid's ability to minimize mission impact against all potential threats to power disruption. The tool considers a realistic set of scenarios that could disrupt power allowing users to compare distributed energy resource (DER) changes against a single microgrid architecture to determine the best balance between cost and resilience. Users can configure the tool to allow for change in microgrid load or updates to equipment costs. A supplemental user's guide provides a thorough walkthrough of the tool, and a supplemental case study demonstrates the tool functionality by analyzing an existing naval installation microgrid.

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
AEMRR	Annual Energy Management and Resilience Report
BESS	Battery Energy Storage System
CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
CI	Confidence Interval
CONOPS	Concept of Operations
DC	Direct Current
DER-CAM	Distributed Energy Resources – Customer Adoption Model
DERs	Distributed Energy Resources
DG	Diesel Generator
DLA	Defense Logistics Agency
DOD	Department of Defense
DoE	Department of Energy
DOE	Design of Experiment
EE	Electrical Engineering
ELMI	Expected Life Cycle Mission Impact
ERA	Energy Resilience Assessment
ESAT	Energy Security Assessment Tool
ESS	Energy Storage System
FOUO	For Official Use Only
HILP	High Impact but Low Probability
HOMER	Hybrid Optimization Model for Electric Renewables
IA	Impact Area
ICSM	Incremental Commitment Spiral Model
LCA	Life cycle Cost Analysis
LCAE	Life Cycle Cost Analysis of Energy
LCC	Life-Cycle Cost

LCOE	Levelized Cost of Energy
LCOED	Life Cycle Cost Analysis of Energy Demand
MDI	Mission Dependency Index
MDT	Microgrid Design Toolkit
MI	Mission Impact
MSET	Microgrid Systems Engineering Team
MTTR	Mean Time to Repair
MW	Mega-Watts
NAVFAC	Naval Facilities
NPV	Net Present Value
NREL	The National Renewable Energy Laboratory
NSETTI	Navy Shore Energy Technology Transition and Integration
O&M	Operation and Maintenance
OR	Operations Research
PV	Photovoltaic
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SAM	System Advisor Model
SE	Systems Engineering
SECDEF	Secretary of Defense
SOC	State of Charge
V	Volts
V&V	Verification and Validation
VoLL	Value of Lost Load
W	Watts
WACC	Weighted Average Cost of Capital

EXECUTIVE SUMMARY

Existing design and analysis tools related to military microgrids lack an integrated system design and analysis process. Currently multiple analyses are conducted separate from one another. The purpose of the Microgrid Systems Engineering Team (MSET) capstone is to integrate electrical engineering (EE) and systems engineering (SE) microgrid efforts into a single cohesive and easy to use Microsoft Excel tool to provide base energy mangers an integrated system design methodology to quickly assess microgrid trade-offs between resilience, cost, and distributed energy resources (DER). The MSET project scope is limited to the integration of existing microgrid tools and models that are freely accessible and focuses on three main topics valued by the stakeholders: resilience, electrical architecture, and cost. Microsoft Excel and freely available existing analysis tools were chosen over closed-source tools and other programming languages so the integrated MSET tool can be easily accessible to and usable by the end users (naval base energy managers).

The MSET tool integrates Oriti's [1] power flow model, Anderson's [2] stochastic resilience model, Hildebrand's [3] cost model, and Peterson's [4] resilience metric—Expected Life cycle Mission Impact (ELMI)—to develop a cohesive tool and methodology for base energy managers to design a microgrid. Oriti's [1] power flow model is intended to correctly size DERs to support a critical load; the power flow graph illustrates how the microgrid components produce power to meet the load demand. Anderson's [2] resilience model introduces stochastic modeling to simulate a power disruption event to assess and quantify the resilience of a microgrid system based on invulnerability and recoverability. A simplified version of Anderson's [2] cost model is used to incorporate the operation and maintenance costs of differing levels of maintenance. Hildebrand's [3] cost model uses the net present value (NPV) and the ELMI resilience calculation developed by Peterson [4] to calculate the life cycle cost of a system. The MSET tool is meant to provide insight into trends of cost, resilience, and DER ratings, and is not meant to provide absolute answers or actual cost quotes. The tool is designed for a single architecture with one photovoltaic array, one battery energy storage system, and one diesel generator expected to support a single critical load. Utilizing a single architecture simplifies the initial analysis of the microgrid by allowing the user to observe the changes in cost and resilience per type of DER.

During the process of testing and execution of the case study, limitations were discovered. The solar irradiance data within the model is set for Spain and is difficult to change. Due to the low granularity of the available cost data in the MSET tool, small changes in DER ratings are not easily represented in the NPV outputs. Additionally, the DER ratings that are correctly sized for the power flow are not suitable for analysis in the "Trade-off Analysis" tab within the Excel tool due to the way the resilience is simulated. The tradeoff analysis configurations are limited to DER sizing that is 50% greater than the average load. Resilience metrics and trends are accurate for DER ratings that fall within 1.5x the average load; however, DERs that are significantly larger encounter difficulty with the way resilience is calculated within the models incorporated in the MSET tool. Another limitation to the MSET tool is the inability to simulate load shedding—the energy management feature that identifies and prioritizes critical and non-critical loads. The aforementioned limitations are good candidates for future improvements to the MSET tool.

The MSET tool provides capabilities not previously available to base energy managers. Prior to the development of the MSET tool, an open source and free tool that takes into account factors that are important to DOD, such as resilience, did not exist. The MSET tool provides initial insight which can focus further analyses and funding. The MSET tool allows the user to choose four different DER rating combinations for a single disruptive event. Although the ELMI resilience metric takes into consideration four disruptive events from the resilience model, the MSET tool reduced the scale of the calculation to consider the mission impact for a single disruptive event.

Preliminary analysis conducted with the MSET tool indicates that in general, increasing the DG rating provided the greatest increase in resilience versus return on investment if fuel availability is not constrained. A DG can provide more power at a lower procurement and operation and maintenance cost than either a photovoltaic or a battery energy storage system (BESS). Analysis conducted during the capstone indicates that it may be possible to further improve the resilience for the DG by increasing the maintenance level up to the supplier's recommended maintenance level; however, these gains are minimal and should be heavily examined in light of cost constraints. Increases to the BESS sizing (e.g.: increased BESS capacity) provide the worst return on investment with a minimal resilience impact at extremely high cost per MSET tool analysis.

The MSET tool is intended to provide the end user the ability to compare and modify military microgrid configurations based on user requirements and restrictions to meet each user's specific circumstance. Several areas of future work have been identified to further improve and integrate analyses that are important to military microgrids. For instance, the tool should be reworked into a more efficient coding language (e.g.: Python) that is better equipped than Excel at running Monte Carlo simulations in terms of computational efficiency. Based on discussions with several commands, Python is quickly being adopted throughout the Navy to support engineering analyses.

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I. INTRODUCTION

A properly constructed microgrid can address the energy security needs of the Department of Defense (DOD) by providing power to critical loads during periods where power from external utilities is disrupted. Previous research and existing tools for microgrid design and assessment address specific aspects of microgrid design and assessment but do not fully assess energy resilience in a context relevant to the DOD. This chapter discusses the problem under consideration and the purpose of this technical report. The background section provides an overview of power generation, energy storage, power distribution, and system control. Chapter I also includes the concept of operations (CONOPS), the scope of the technical report, and a stakeholder analysis.

A. PROBLEM STATEMENT

The Secretary of Defense (SECDEF) is required to "ensure the readiness of the armed forces for their military missions by pursuing energy security and energy resilience" [1]. Additionally, the SECDEF has authorized the use of energy resilience and energy security factors to drive cost-benefit analysis for energy procurement, and to favorably consider "projects that will use renewable energy sources to provide power to military facilities or to an installation's electrical grid. Consequently, all military microgrid decisions must consider trade-offs between energy security and the cost of the energy" [2].

A variety of commercial and academic tools exist in literature and are commercially available to understand civilian microgrid infrastructure from the perspectives of reliability, economics, resilience, and other important "ilities." However, existing design and analysis tools related to military microgrids lack an integrated system design and analysis process. Base energy managers lack a cohesive methodology or toolset to assess energy resilience, security, or needs without cobbling together tools or modifying commercially available software for DOD purposes.

B. PURPOSE

The purpose of the Microgrid Systems Engineering Team (MSET) capstone is to integrate electrical engineering (EE) and systems engineering (SE) microgrid efforts into a single cohesive and easy to use Microsoft Excel tool to provide base energy mangers an integrated system design methodology to quickly assess microgrid tradeoffs. Integrating both EE and SE efforts merges key pieces of information synthesized by multiple diverse studies, ensuring each discipline will be able to concentrate on their own domain while using beneficial inputs from the other, creating a synergistic effect. Thus far, EE efforts approached microgrids from a power flow perspective while SE efforts approached microgrids from a resilience and cost perspective. This capstone seeks to reduce rework performed by end users who currently manually integrate tools and methodologies to perform assessments. The team develops a more streamlined and comprehensive process based off prior EE and SE research enabling the base energy managers to assess the resilience and trade-offs of microgrids on military installations.

C. BACKGROUND

The U.S. Department of Energy (DoE) defines microgrids as "a group of interconnected loads and distributed energy resources (DERs) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid" [2]. "A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or [grid-disconnected] island mode" [3]. The early 2000s established the concept of a modern microgrid as a power system served by utility power that can continue to provide power in island mode operation using DERs [4], [5]. DOD policy and objectives were established to define goals for the percentage of renewable power and encourage its increased usage as well as ensure the armed forces address energy security and resilience [1].

Energy security is critical to address for naval installations due to the strategic importance of loads. National security necessitates that bases continue to meet mission requirements under degraded energy conditions; energy security is typically characterized by the "ability to supply critical loads reliably, indefinitely, economically, and in an environmentally friendly manner (sustainably), which enables full-time mission support"

[6]. Because many DOD functions and activities are reliant on the ready availability of energy, "the issue of energy security must be addressed in a systematic and systemic way to assure mission accomplishment" [2]. There are two categories of functions that require readily available energy on a naval installation—critical functions defined as necessary to support the installation's mission and non-critical functions defined as any loads that are not considered critical. Installations may designate critical functions differently based on their intended mission sets.

For naval installations, the Naval Facilities (NAVFAC) generally controls the base microgrid, which is capable of functioning whether connected to an external power provider. A microgrid can operate while connected (grid-connected mode) to, or disconnected (island-mode) from the external (civilian) utility grid [3]. In grid-connected mode, if the power demand of the installation load is high, the microgrid draws power from the public utility grid to fulfill demand. In contrast, if power demand of the loads is low, the microgrid may supply surplus power to the utility grid, may store surplus energy in on-site energy storage systems, or may curtail local energy production to match demand. In the event of an emergency or disruption due to natural disaster, power shortage (e.g., rolling blackout, public safety power shutoff, etc.), or an adversary attack, the microgrid can transition to island-mode. "In island mode, the microgrid is isolated from the local utility and assumes responsibility for actively maintaining microgrid voltage and frequency within agreed upon ranges" [2].

The DOD has a vested interest in improving energy security; one of these measures being to strengthen electrical power system resiliency against natural disturbances, faults, or deliberate attacks [7]. DOD facilities can utilize microgrids to improve resilience as they mitigate the effects of power interruptions as well as improve "the ability to continue to meet critical electrical loads when utility power is lost" [8].

This technical report focuses on the island-mode of a military microgrid to properly perform a utility independent assessment. In order to operate successfully in island-mode, the microgrid system generates power, stores energy, distributes power, and performs control functions [2]. Each of the functions is elaborated upon in the following Chapters I.B.1 - I.B.4.

1. Power Generation

The majority of microgrids contain one or more DER; local energy generation sources often take form as conventional fossil fueled generators, alternative fueled generators, or renewable energy sources [2]. When the external grid connection is disrupted, grid-connected military microgrids rely heavily on diesel generators (DGs) with the addition of photovoltaic (PV) systems as a source of renewable power. PV systems utilize the sun to generate power but are ineffective generation sources during periods of darkness or during periods of inconsistent sunlight. This report will include DGs as the most prevalent and consistent backup power generation source and PVs as a common renewable generator. The PV element in the system can be considered a relevant placeholder for any assortment of alternative power generation options available to a site energy manager, selected based on location.

2. Energy Storage

The integration of multiple power sources within a microgrid provides greater redundancy to ensure missions and operations are uninterrupted. However, power generation is not the only issue of concern. The operation of DGs depend on a steady fuel supply, and PV operation is highly impacted by solar irradiance, which is not always consistent. As a result, there is a need to store energy during peak power generation so it can be used when the power generators are unable to meet the load demand. Many options are available for energy storage. Most recently, alternative energy storage system (ESS) technologies such as thermal, kinetic, and gravity based ESSs have been developed [9], [10]; however, many are still new and yet unproven. The most common ESS used in the military today are chemical batteries. This choice is primarily due to the DOD's interest in demonstrated, reliable technology, especially for the purpose of maintaining energy security [11].

3. Power Distribution

Power distribution is accomplished through electrical transmission lines and electrical buses. Alternating current (AC) "energy transmission is generally used when there are longer distances between nodes in the microgrid network. Direct current (DC) energy transmission is often found in specialized microgrid applications such as computer server farms or facilities with large quantities of sensitive electronics." [2]. As AC energy is generated and distributed across the network, transformers are used to "step up" or "step down" voltage levels to convert AC energy to the required voltage. Switches and breakers are also necessary so loads can be energized and de-energized depending on the system's status. DER and battery ESS also require the use of power electronic devices, or power converters to convert voltages from AC to DC, DC to AC or DC to higher or lower DC voltages.

a. System Control

Microgrid system control (or energy management system) is accomplished through a controller that can command the DER and ESS. Microgrid controller logic is outside the scope of this report and the number of controllers will not be considered. The controller will dictate how much power is generated by the DGs and/or DER as well as the flow of power into and out of the ESS. The controller can generally also sense when utility grid power is lost, and often automatically sheds any non-critical loads. Load shedding is done through the control logic for the system controller, which dictates what loads are supported in island-mode (critical loads) and what loads may be optionally supported (non-critical loads).

To assess installation requirements, the base microgrid must identify and separate the non-critical loads, which enables the microgrid to keep critical loads online during a destabilizing event. Ideally, the separation of critical and non-critical loads is desired; however, not all base microgrids are configured this way. Base energy managers must be able to correctly identify the critical installation loads. This report assumes that non-critical loads have been identified and can be separated from the power supply during periods of excess demand.

D. CONCEPT OF OPERATIONS

This section differentiates between the CONOPS for a generic microgrid required for background knowledge and the CONOPS for the MSET tool that was developed as part of this technical report. The CONOPS for both general microgrids and the MSET tool serve as the fundamental foundation on which the tool is developed.

1. Microgrid CONOPS

A microgrid is defined as a power generation and distribution system capable of working while either connected to or disconnected from the external utility grid. For this report, it is assumed that the microgrid under assessment is configured, as shown in Figure 1.

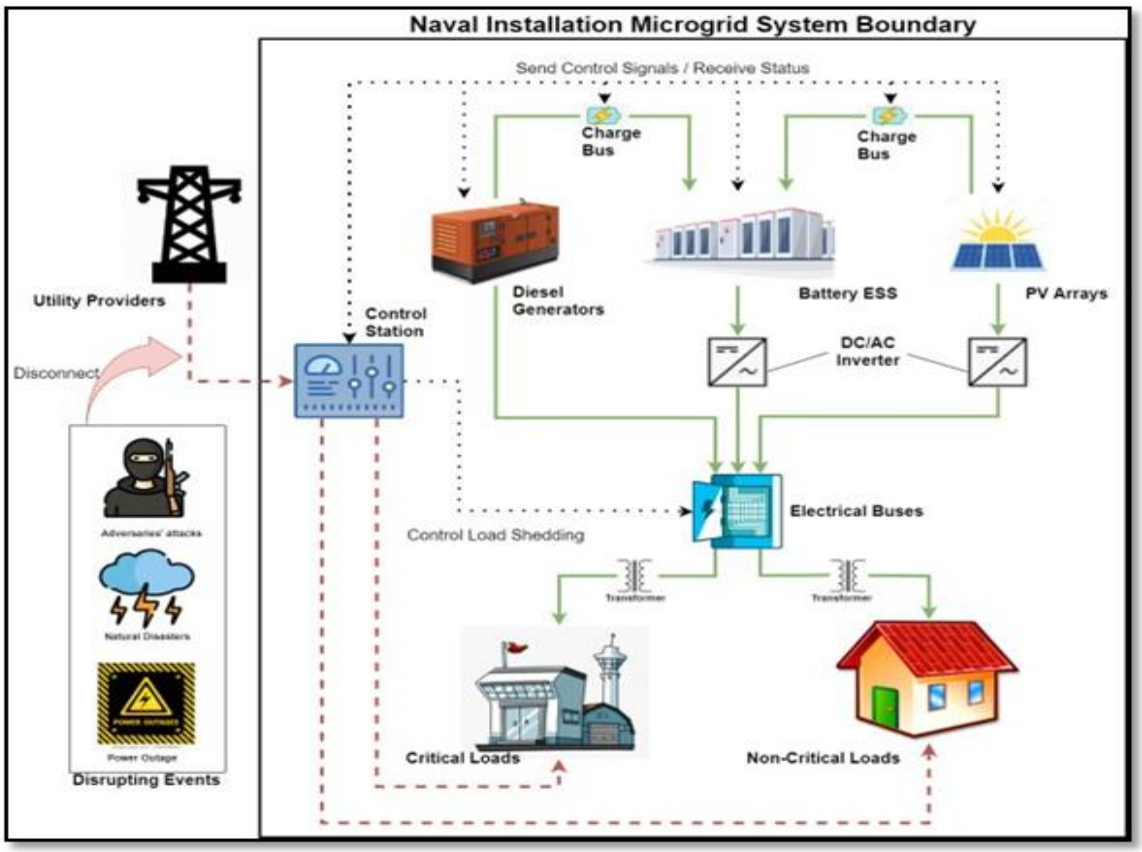

Figure 1. Basic Microgrid Concept of Operations (CONOPS)

The microgrid CONOPS addresses interactions for basic components and entities for a simplified microgrid. The intent is to provide the general characteristics and relationships for a general overview. The smaller internal black box is the boundary for the microgrid on the naval installation. Under normal conditions, military installation microgrids are powered by an external utility grid which provides the power to the naval installation. At this time, the PV array and/or DGs keep the batteries charged as backups, but they do not carry loads. When the control station senses an external utility grid disruption, island mode is initiated in which all loads on the base microgrid are shifted to be carried by the DER sources on base.

When in island mode, if the power demand exceeds the power supply, the non-critical loads are shed so the available DER can continue to support the critical loads. If the microgrid and the control logic are designed properly, the critical loads will remain powered for the required period of autonomy.

2. MSET Tool CONOPS

Several commercial and academic microgrid assessment tools currently exist. Navy Shore Energy Technology Transition and Integration (NSETTI) has funded NPS to design several microgrid analysis tools and methodologies. The NSETTI tools were developed to assist with PV and battery sizing with variables for solar irradiance, PV loss due to weather, duration of outages, and DER backups. NSETTI continues to collaborate with NPS to develop tools to calculate microgrid resilience, resilience cost analysis, and evaluating recovery actions, which dovetail nicely with previous tools developed as part of the NSETTI project.

The tool developed by MSET provides a single interface that integrates several previously developed SE and EE tools (largely through the NSETTI Project) to assess microgrid designs more easily for specific conditions. Base energy mangers are the intended users as they are responsible for the supply and support of power to the command installation. The base energy manager user provides the MSET tool the necessary inputs in the requested format. These inputs will be fed into the various SE and EE tools developed to date and will produce their respective results and recommendations, which will be simplified and consolidated in the MSET tool outputs.

E. SCOPE

The MSET project scope is limited to the integration of other existing microgrid tools and models that are freely accessible. During the literature review, it was decided to avoid the use of any tool sets that required licensing or special software. Given those limitations, MSET determined certain research efforts were more aligned with MSET's intended direction. Through the integration of different engineering disciplines, the tool is intended to provide sufficient information to the base energy manager (the end user) to allow them to determine the best configuration balance and trade-off for their installation and situation. Figure 2 is the context diagram developed by MSET for this work.

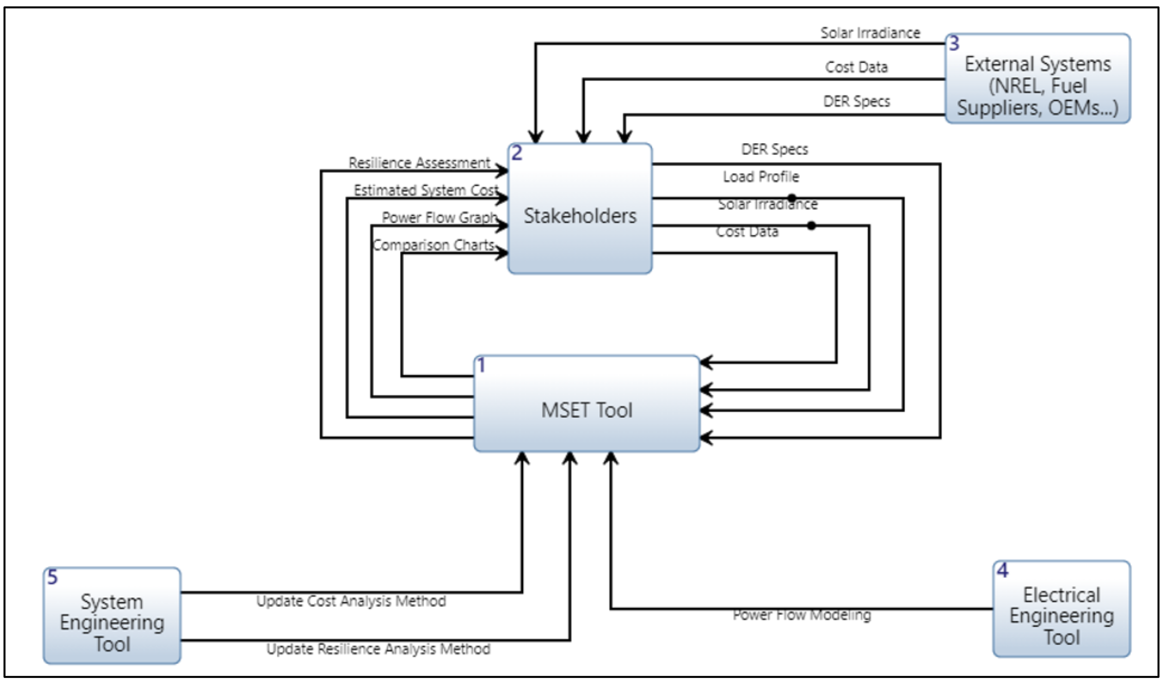

Figure 2. Context Diagram of the MSET Tool

MSET expected to iteratively expand the scope of the project to gather the necessary information and to close deficiencies discovered during tool creation. MSET's scope is bounded to the integration of existing research and toolsets; any deficiencies left unresolved, missing tools, or dead ends discovered during development will be documented and discussed in future work.

F. STAKEHOLDER ANALYSIS

NPS has collaborated with stakeholders to develop several analysis tools and methodologies to assess electrical engineering and resilience analyses of microgrids. This report outlines and details the process and analysis for the development of the MSET tool developed as an NPS Systems Engineering Department capstone project. Stakeholders include those that have an interest in using the integrated tool and/or funding the development of this project. Stakeholder analysis was performed with the capstone advisors to determine how previous work, knowledge base, and high-level interest/needs tie into the overall goals of this project. This information was used to develop and refine the purpose, scope, requirements, and end results of this report. Top level SE diagrams were produced and presented to project advisors to ensure MSET developed a microgrid resilience analysis tool that was in line with stakeholder requirements and needs. Table 1 lists the different stakeholders interested in the microgrid.

Table 1. Stakeholder Categorization

Microgrid Stakeholders		
Primary	**Secondary**	**Tertiary**
Facilities / Personnel	Electrical Utility	Installers
Facilities Managers	Supply System / Personnel	Equipment Manufacturers
Utilities Managers	Maintenance Activities	Surrounding Community
Owner		

Stakeholders are broken into three different categories: primary, secondary, and tertiary. Primary stakeholders have the greatest interest and direct usage of the MSET tool while secondary and tertiary stakeholders are expected to be affected by decisions. The primary stakeholders include the personnel within the installation that receive power from the microgrid system and are responsible for determining the mission and load criticality of contributing system, the facilities and utility managers responsible for the infrastructure within the installation to include acquisition and sustainment serving the needs of functions performed at the installation; and the owner of the microgrid who is funding the microgrid [12].

Secondary stakeholders include the local utility provider, supply system/personnel and maintenance personnel and systems, these stakeholders determine integration boundary constraints such as physical coupling, "power supply limitations, power quality, disconnection and reconnection parameters, and ability and limitations on exporting excess power back to the utility grid" [12]. Maintenance personnel and supply systems will determine supportability limitations such as availability of spares, timeline and ability to perform inspections, maintenance, diagnostics and repairs [13].

The tertiary stakeholders such as equipment manufacturers, installers, and the surrounding community are loosely interested in the system because it provides a source of revenue. Each military installation with an operational or developmental microgrid has different stakeholders that install, manage, and maintain the microgrid, or in the case of the surrounding community may be impacted in some manner due to power interdependencies. The equipment manufacturer and installers are heavily involved in the initial acquisition and implementation and will be involved in providing interface data and determine interoperability between systems and may continue their involvement to provide updates, support maintenance, repairs, and other activities through the duration of the microgrid life cycle [12].

The MSET tool has four primary and two secondary stakeholders. Table 2 lists the stakeholders interested in the tool MSET has developed.

Table 2. MSET Tool Stakeholders Categories

MSET Tool Stakeholders	
Primary	**Secondary**
Dr. Van Bossuyt	NSETTI Project Team
Dr. Oriti	NAVFAC EXWC
Dr. Giachetti	
Energy Managers	

Based on the scope of the capstone project, MSET interacted primarily with the advisor Dr. Douglas Van Bossuyt, and co-advisor Dr. Giovanna Oriti. Dr. Ronald Giachetti, System Engineering Department Chair, is a microgrid systems engineering subject matter expert as well as a primary stakeholder. The intended user of the MSET tool is the base energy manager, who is the main primary stakeholder; however, MSET does not have direct contact with an energy manage. Secondary stakeholders are the NSETTI project team, who are interested in the outcome of the toolset for further study.

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II. LITERATURE REVIEW

This chapter presents relevant work produced by a variety of sources that have a significant impact in the overall MSET purpose. In literature reviews performed by MSET, a variety of resilience definitions, methods, and aspects were discussed. Chapter II.A covers resilience definitions and metrics; Chapter II.B covers the electrical architecture of microgrids; Chapter II.C covers the cost of microgrids and the cost of microgrid resilience; Chapter II.D covers trade-offs between different definitions and sources explored earlier.

A. RESILIENCE

There are many interpretations and definitions of resilience. Chapter II.A.1 collects and summarizes relevant definitions of resilience from the public and private sector perspectives while Chapter II.A.2 covers the different metrics of resilience. Once the various definitions and metrics have been introduced, the definition and metrics that best fit the purpose of the MSET capstone project will be identified.

1. Resilience Definitions

DOD Instruction 4170.11 defines energy resilience for DOD facilities as "the ability to prepare for and recover from energy disruptions that impact mission assurance on military installations" and critical energy requirements as "critical mission operations on military installations or facilities that require a continuous supply of energy in the event of an energy disruption or emergency" [14]. This is in line with a similar definition found in the Department of Defense Annual Energy Management and Resilience Report (AEMRR) for fiscal year 2017, which utilizes the definition of energy resilience found in 10 U.S. Code § 101(e)(6):

> The ability to avoid, prepare for, minimize, adapt to, and recover from anticipated and unanticipated energy disruptions in order to ensure energy availability and reliability sufficient to provide for mission assurance and readiness, including task critical assets and other mission essential operations related to readiness, and to execute or rapidly reestablish mission essential requirements. [14]

Anticipated and unanticipated energy disruptions can include adversarial actions, extreme weather events, or natural disasters. The report further asserted that multiple methods can achieve energy resilience with microgrid application, including storage of energy which is key to a system's ability to absorb a disruptive event without dropping all loads.

Additionally, DOD "doctrine prescribes resiliency using a days of autonomy metric. For naval facilities, this metric is seven days of autonomy as driven by UFC 3–540-01, which dictates the amount of onsite fuel storage for backup generators" [15]. The U.S. armed forces established metrics for critical mission support; to be considered resilient, a DOD microgrid system must support critical loads directly after a disruptive event as well as pre-defined amount of time after. Installations must last 14 days for the Army and Marines. UFC 3–540-01 dictates that seven days of autonomy are required for naval facilities [15].

The NAVFAC P-602 provides a resilience definition from the standpoint of naval facilities. The P-602 addresses types of disturbances that could be relevant for energy security at naval facilities, and further ties the concept of resiliency to mission:

> Resiliency is the ability of a system to anticipate, resist, absorb, respond, adapt, and recover from a disturbance. Threats that may cause a disturbance include weather events, accidents, geo-magnetic storms, terrorism, fire, cyberattack, and the effects of climate change e.g., sea level rise. Energy resiliency will ensure DON installations have the ability to both prepare for and recover from utility interruptions that impact mission assurance and installations. [16]

Yodo and Wang's "In Engineering Resilience Quantification and System Design Implications: A Literature Survey" discusses the development of a general analysis framework with a focus on engineering resilience that can be utilized for system design. Yodo and Wang [17] start by introducing an ecological definition of resilience, "resilience in an eco-system is defined as the speed with which an ecosystem returns to its equilibrium state following a perturbation" [18]. The concept of resilience in engineering has been strongly influenced by the ecological idea of how quickly the system can be returned to equilibrium. In engineering, after a disruptive event, equilibrium refers to the speed at which a system can adapt and recover from that state of disruption. Based on this definition of resilience, Yodo and Wang introduce the engineering resilience curve, Figure 3.

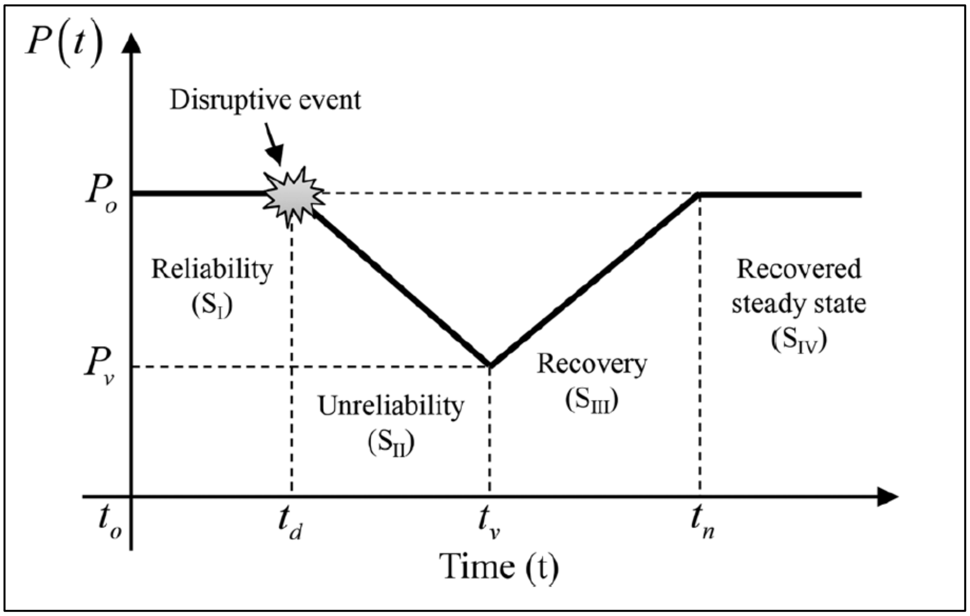


Figure 3. General Resilience Curve with Four States. Source: [17].

In Figure 3, the bold line represents the system performance over time. The performance is constant until a disruptive event occurs, at which point the system's performance drops to some degraded state. In the Figure, the system performance degrades at a constant rate until recovery takes place at time t_v, then the system performance increases at a constant rate until performance returns to the pre-disruptive state. This is an idealized curve because of the linear degradation and recovery; a real-world example could have convex, concave, linear, or non-linear unreliability and recovery profiles as shown in Figures 4 and 5. Figure 4 shows only the different recovery profiles. Figure 5 provides the most realistic resilience curve with a nonlinear unreliability and recovery profile with no stabilization in a degraded state.

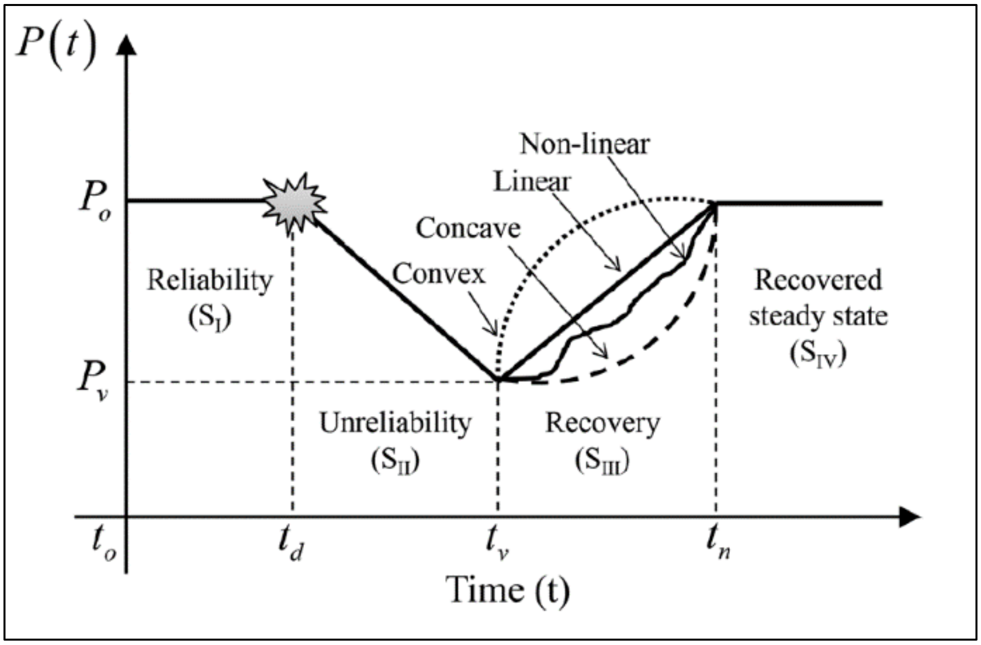


Figure 4. Depiction of Various Unreliability. Source: [17].

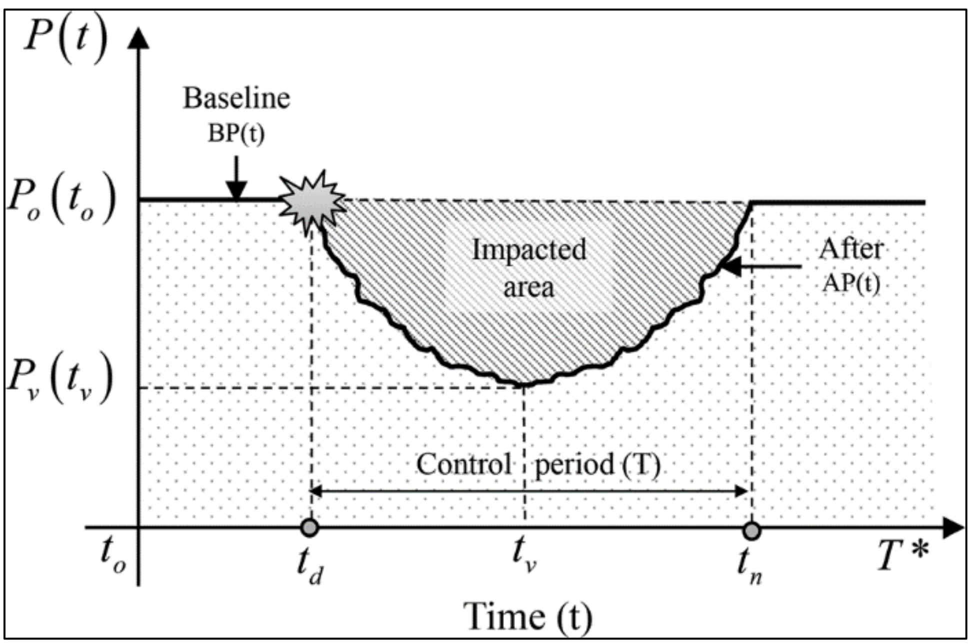


Figure 5. Recovery Profiles Possible for Resilience Curves. Source: [17].

The possible unreliability and recovery profiles depicted in Figure 5 provide a more realistic perspective of an engineering resilience curve following a disruptive event as it is unrealistic to assume engineered systems will follow a linear unreliability and/or recovery profile. Yodo and Wang continue to build on this profile for a more realistic resilience curve, which is called the Five State Resilience curve, as shown in Figure 6.

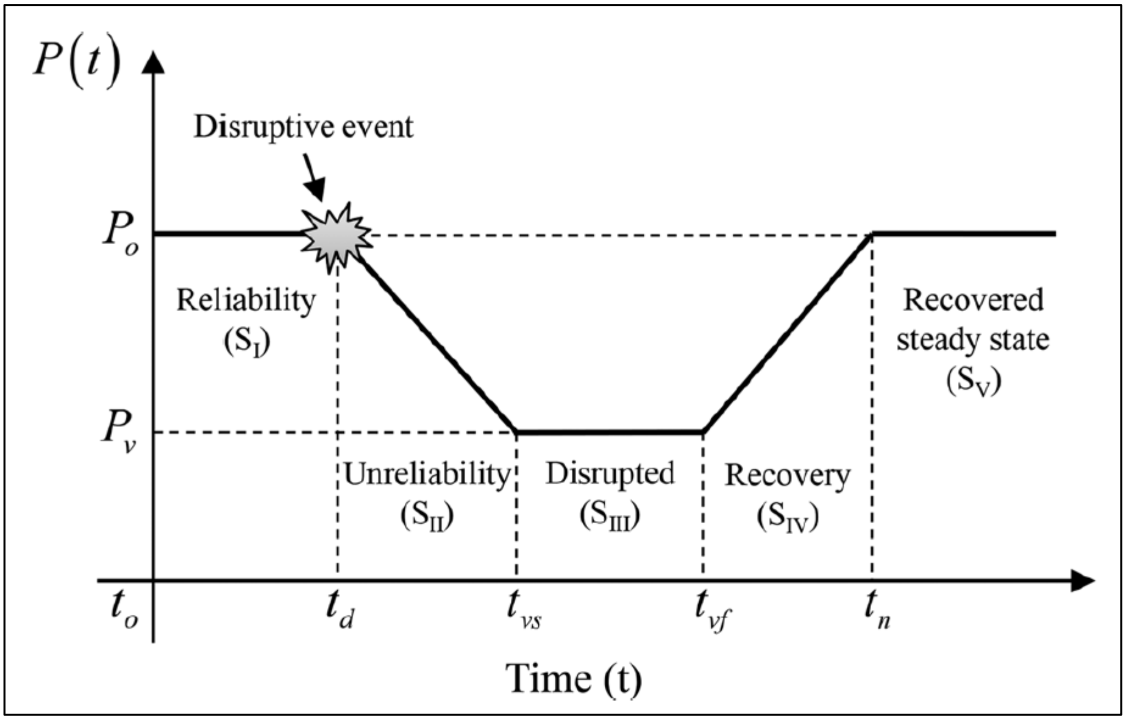


Figure 6. General Resilience Curve with Five States. Source: [17].

The key difference between Figure 5 (four-state curve) and Figure 6 (five-state curve) is the addition of the steady disrupted state depicted by S_{III}, which equates to a stabilization period prior to proceeding to a recovery state.

The microgrid resilience curve introduced by Anderson is very similar with slightly different terminology and is more focused for DOD applications, which is a better fit for MSET research. The resilience curve depicted in Figure 7 is Yodo and Wang's five-state resilience curve which differs from their previous curve with the addition of a high impact but low probability (HILP) disturbance that results in microgrid performance degradation and limited to a single scenario (e.g., one hurricane, tornado, etc.). The performance of a microgrid is defined by the percentage of the load demand carried by that microgrid [19].

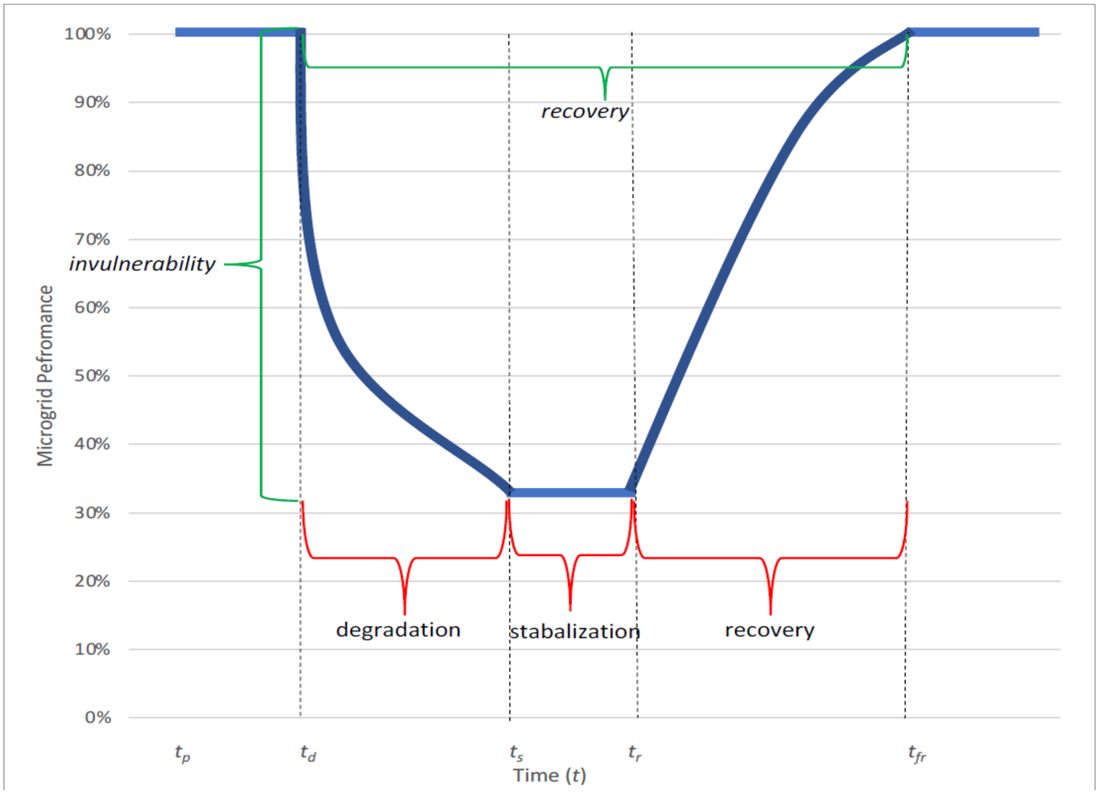


Figure 7. Microgrid Resilience Curve. Source: [19].

The re-creation shown in Figure 7 incorporates more descriptive and meaningful labels for the five different states that occur during a disruption scenario. Invulnerability represents the overall loss of microgrid performance caused by a disruptive event. The green recovery across the top of Figure 7 represents the time required for a microgrid to recover from a disruptive event to the pre-disruptive level of performance. Anderson's invulnerability is the same as the impact area described by Yodo and Wang, who consider resilience from the perspective of recoverably and reliability [17]. Anderson, however, primarily focuses on recoverability, defining resilience as the "microgrid's invulnerability and rapid and full recoverability from an improbable and severe disturbance" [19].

Peterson's resilience definition also draws from the same sources summarized at the beginning of the literature review, and can be defined as the "ability of the system to maximize functionality in the event of a disruption...by considering both likelihood and impact of each disruption" [12]. The literature review performed by MSET determined that a combination of both Anderson and Peterson's definitions of resilience best suits MSET's needs. MSET defines microgrid resilience as a microgrid's invulnerability and a rapid and full recoverability from an improbable and severe disturbance while maximizing functionality in the event of such a disturbance. Maximizing resiliency means the system provides the maximum functionality possible against the entire set of potential disruptions, considering both the likelihood and impact of each disruption [12], [19].

2. Resilience Metrics

Yodo and Wang provide excellent insight on the profile of resilience curves as well as metrics by which one can measure resilience. Their work introduces three different resilience metrics:

1. "Resilience metrics based on resilience curve" [17]
2. "Resilience metrics based on pre- and post-disruption" [17]
3. "Resilience metrics based on reliability and restoration" [17]

Yodo and Wang's first quantification method uses properties of the resilience curve, primarily the impact area (IA), as seen in Figure 5. The IA is the area of the curve that indicates performance loss due to a disruptive event and can be derived mathematically using integrals.

The second way to quantify resilience is to use a ratio that represents the change in a system's performance from pre-disturbance to post-disturbance. However, expressing resilience in this manner shows that performance is extremely dependent on the system and its use. Every microgrid, installation, and power requirement are unique and therefore, resilience parameters based on pre- and post-disruption are only useful for doing a self-comparison, so this metric will not be discussed or utilized.

The final methodology Yodo and Wang describe is based on restoration and reliability explains,

> A mathematical formula has been derived to quantitatively measure the resilience of engineered systems with two essential attributes as reliability and restoration, in which system reliability quantifies the ability of an engineered system to maintain its capacity and performance above a safety limit during a given period of time under stated conditions, whereas restoration measures the ability of an engineered system to restore its capacity and performance by detecting, predicting, and mitigating/ recovering from the system-wide effects of adverse events. [17]

The third metric that Yodo and Wang discussed for resilience of reliability and restoration aligns best with MSET's determination of how military microgrid resilience should be measured. Yodo and Wang's work will be the foundation with which the MSET tool is developed, both a clear understanding of their resilience definitions will be necessary in the assessment of how and if the tool can be integrated with the MSET power flow and resilience tool.

In addition to resilience metrics defined by Yodo and Wang, Panteli et al. [20]. developed the ΦΛΕΠ (FLEP) to model and quantify resilience performance of a microgrid after a catastrophic event. As seen in Figure 6, the shape of the curve found between t_d and t_n, is described by Panteli et al. as the "resilience trapezoid," which he further segregates into three phases, as seen in Figure 8.

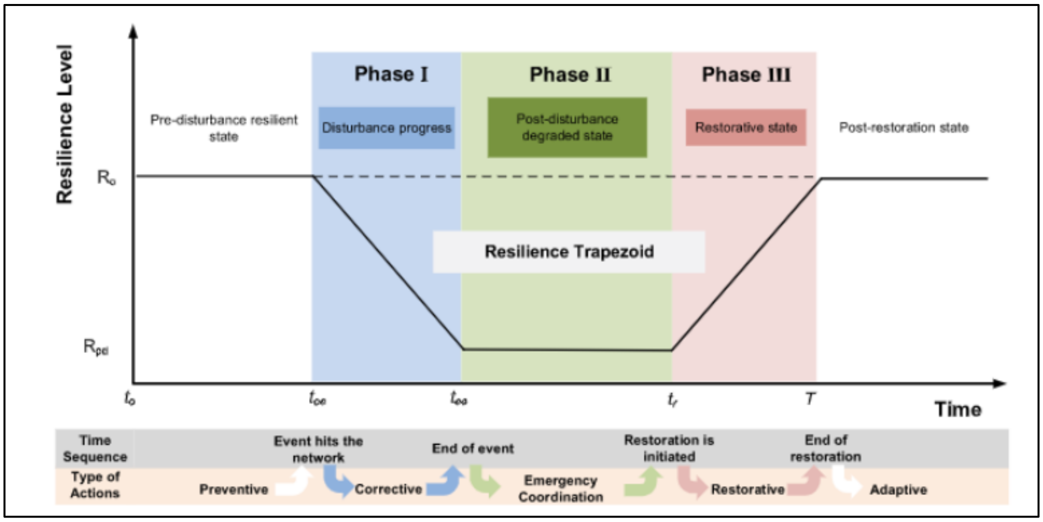


Figure 8. Panteli et al.'s Depiction of the Resilience Trapezoid. Source: [20].

Phase I or Disturbance Progress, is intended to measure how quickly resilience drops (Φ), as well as how low it will drop (Λ). Phase II, the post-disturbance degraded state also known as the stabilization state measures (E), the length or extensiveness of the degraded state. Finally, Phase III, the restorative state, measures (Π), which is how quickly the microgrid can return to its pre-disturbance state of performance [20].

Current microgrid literature is abundant in resilience metrics. As Anderson states, "there is little-to no understanding of what design components are most useful to enhancing resilience for off-grid microgrids" [19]. Anderson's paper reviews the Energy Resilience Assessment (ERA) tool and the Energy Security Assessment Tool (ESAT) intended to assess resilience for a base power grid. However, these tools were determined to be of limited use as they fail to provide sufficient or meaningful data for the resilience assessment of a naval installation microgrid that has lost connection, or never had connection, to an outside utility provider, the very circumstance MSET seeks to address.

There have been numerous attempts from researchers to assign proper metrics for resilience in electrical power distribution systems. The common ground among their work is that resilience is considered a time-dependent performance function. From this shared definition, each researcher proceeded to develop their own independent resilience metrics.

One approach to calculate resilience based on loss was developed by Li et al. [21]. The authors measure the resilience curve using resilience = (1/loss), where loss is calculated as

$$loss = \int_{t_1}^{t_\Delta} \left(\frac{Q_0 - Q(t)}{Q(t)}\right) dt \tag{2.1}$$

Loss is determined by the ratio of largest performance loss due to a certain disrupting event and the current performance state over a long period of time [19].

Zobel calculates resilience by taking a percentage of total possible loss X at disruption time T over the time required to fully recover [22]:

$$R(X,T) = 1 - \frac{XT}{2T^*} \tag{2.2}$$

However, the weakness in this methodology is that it is only useful to determine the resilience of a microgrid at a defined moment and does not account for a measurement of resilience over an extended period [19].

The metrics introduced in Equations 2.1 and 2.2 do not account for the stochastic behavior of disruptive events that affect the resilience of microgrids. Anderson [19] has presented many cases where the researchers utilize predictive modeling for system performance factors that influence system performance in the measurement of resilience. He utilized a code-based metric for time durations that considered outage durations and spatial impact. MSET considers this metric overly complex with limited improvements to the product, so there is no current intent to include it in the product.

The National Renewable Energy Laboratory (NREL) uses value of lost load (VoLL) for a resilience metric. VoLL is a resilience metric that factors in costs, this could include business interruption costs, recovery costs, or losses of perishables or assets [23]. Though considering resilience in terms of a dollar cost value is very intuitive, it has limited application. Anderson et al. [19]. narrowed down the VoLL to applying for loss of critical load, L_c, during the disrupting period T:

$$VoR = Voll \int_0^T L_c(t) dt \tag{2.3}$$

Traditionally, reliability has been the greatest focus of resilience efforts [17]. Accordingly, several established metrics regarding reliability such as System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), and Customer Average Interruption Frequency Index (CAIFI) for electrical power grids. However, a recent report by Sandia points out the shortcomings of solely using these metrics, as they "typically do not include outage information when low probability, high-consequence events such as storms, earthquakes, and cyber-attacks occur" [19]. The reports also suggest a metric based on the consequence of a specified hazard for resilience.

Many of the metrics reviewed focus on monetary value or loss in performance. Fewer metrics address readiness or mission achievement. Because national security is a complex consideration for military installations, mission-oriented metrics should be a significant driver in assessment of microgrid design. Work by Judson, Pina, and Dydek defines the resilience by considering the "cost to relocate the mission or buy services to complete mission" [24]. Since this definition would be base- and mission- specific, it would be incredibly difficult to quantify and was deemed inapplicable for MSET's purposes. Relocation or service purchasing costs are also impractical for a scenario where the base experiences an attack from an adversary. Scenarios such as this do not lend themselves to either moving the mission or purchasing the necessary services from an external entity as a viable solution, as such, this defined value of resiliency cannot be utilized by MSET.

NAVFAC utilizes an operational risk metric called the mission dependency index (MDI), a method that quantifies a value based on a series of questions posed to indicate the consequence or impact if a facility is either destroyed or becomes non-functional [25]. Kujawski and Miller [26] identified major limitations in MDI-related metrics such as poor resolution, failing to quantify probability or likelihood, inconsistency in application, and failing to consider the time dependency of any corrective actions.

The methodology by Peterson [12] uses MDI concepts and assigns a quantifiable value to the mission achievement tied to a specific power load. He uses an Expected Life cycle Mission Impact (ELMI) that quantifies system resilience by calculating the total impact of disruption events over the expected lifetime. Once ELMI is established for a scenario, ELMIs can be evaluated to determine the main drivers that affect mission impact. Peterson's model estimates facility loads and PV power generation and simulates the microgrid "in hourly time steps to determine the microgrid system response, load shedding, and the subsequent mission impact in each scenario through Monte Carlo simulation methods" [12]. The user can iterate the model analysis for different architectures, generating alternate design ELMIs for direct comparison.

B. ELECTRICAL ARCHITECTURE

Important EE considerations for microgrids address design details and operability efficiencies. EE research has developed tools to conduct power flow analysis and distributed energy resource design. These tools are intended to assist base energy managers in the design of military installation microgrids from an electrical standpoint.

Siritoglou [6] presents a design methodology for DERs that a facility manager can use to verify the performance requirement of a microgrid. This methodology is implemented in a graphic user interface tool developed in MATLAB Simulink, which was intended to be user-friendly. The tool is simulated and validated by physics-based models and experiments with microgrids built using COTS components. These components and their configurations comply with both IEEE Standards 1562–2007 and 1013–2007. The design methodology starts with determining the load, without specifying criticality. Predetermined days of autonomy and battery efficiency are considered along with the load to determine the optimal number and configuration of batteries. Siritoglou's model then calculates the most efficient microgrid PV array design based on the historical data of solar irradiance at the location of the base. It uses the array-to-load ratio as an input and outputs the number and configuration of batteries and PV arrays which can then be assembled into a microgrid architecture, as in Figure 9.

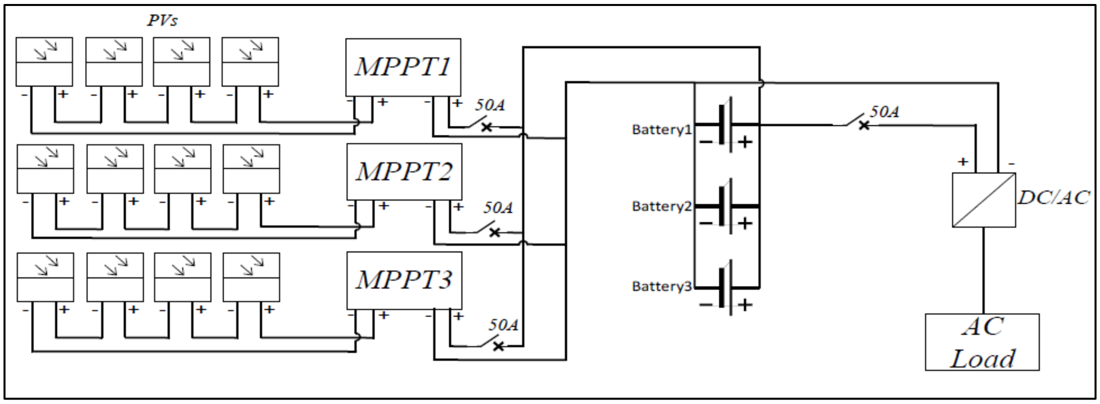


Figure 9. Architecture of the COTS Microgrid. Source: [6].

Siritoglou validated his design methodology by comparing his model simulation's outputs against the outputs of an experimental COTS microgrid design assembly. He conducted two scenarios, 24-hour autonomy with and without sunlight, and analyzed the battery's state of charge (SOC) to compare the simulation and experiment. As seen in Figures 10 and 11, the curves for the simulation and experiment are closely matched, indicating that Siritoglou's DER design methodology is valid and accurate.

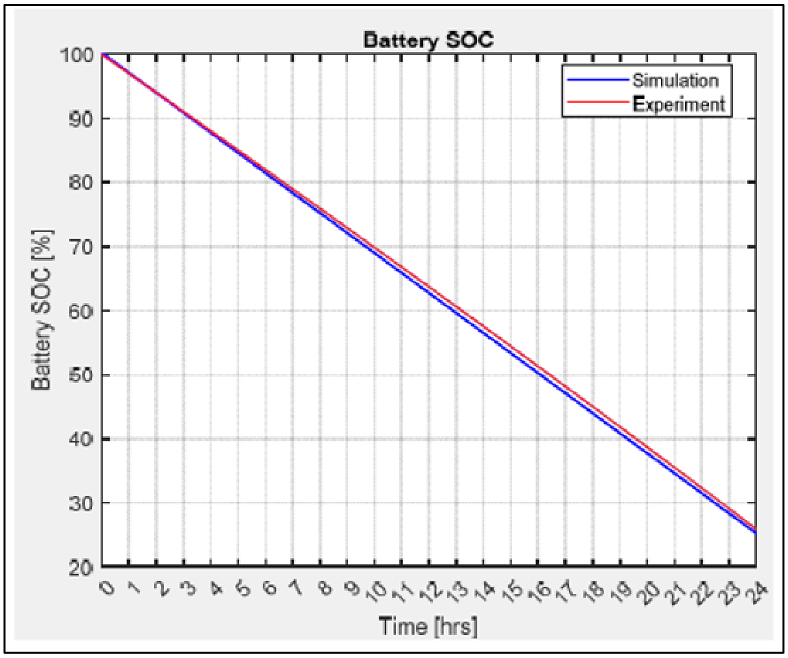


Figure 10. Battery SOC (Without Sunlight). Source: [6].

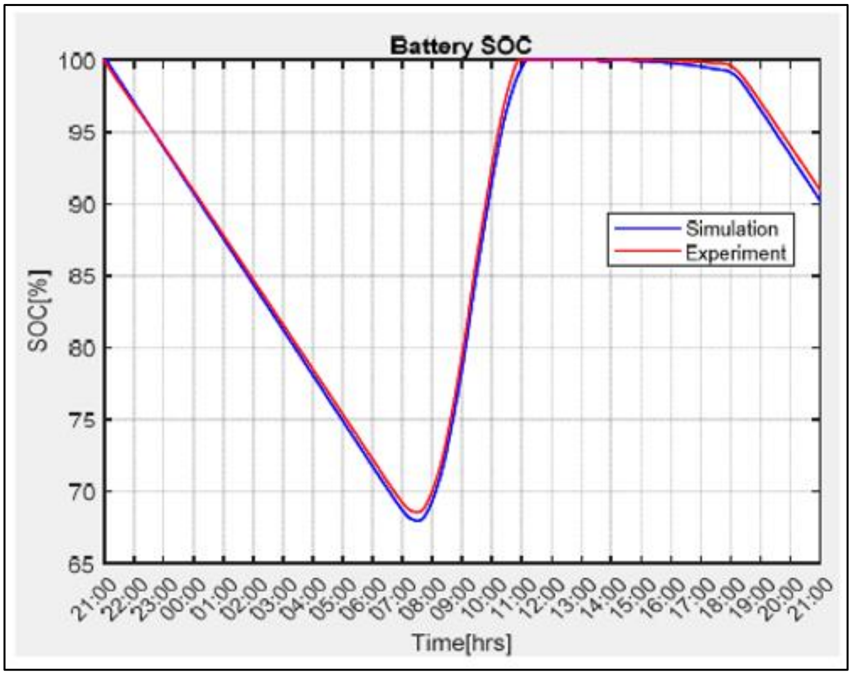


Figure 11. Battery SOC (With Sunlight Using Experimental PV Current). Source: [6].

Siritoglou’s model provides for several variations in input; however, its base software is a detriment to its utility because MATLAB is a specialized software not readily accessible nor familiar to base energy manager end users. Ruth Fish [27] expanded upon Siritoglou’s model and toolset to create the design model in Microsoft Excel and proved its applicability with multiple case studies.

By converting Siritoglou’s model to a more common format, Fish’s Excel tool has greater utility for the intended energy manager users as the Microsoft Office suite is common to most computers across the DOD. Fish’s design tool considers options for the PV array, battery bank, and the fuel and generator storage. This tool exists in two variants: the automatic variant, which calculates the number and sizing of battery and PV arrays using commercially available component data sheets; and the manual variant, which allows the user to customize the battery and PV specifications individually.

Fish’s tool further calculates the number of generators needed for the system. She considered greater efficiency the key consideration for generator sizing with a PV integrated microgrid. The efficiency of the generator is directly related to the output power produced by the generator. The tool utilizes the rated generator power and the maximum load power to calculate the minimum number of generators needed to operate the system. Fish provides pre-selected generator models with distinctive functions, capabilities, and limitations. The fuel storage in Fish's toolset is dependent on the user's required duration of system operation. The tool will determine the amount of fuel necessary to operate the system autonomously for the desired period given the determined generator fuel burn rate.

The model created by Fish uses active power balance equations so that the sources and load power curves can be plotted versus time. By simulating the power flow, base energy managers can identify patterns and discrepancies where power is deficient or in excess, pinpointing weaknesses in the microgrid design. Her work was validated on a microgrid built with commercial off the shelf (COTS) components.

C. COST

Most existing microgrid optimization research tends to focus on prioritizing cost factors and objectives. There has been significant effort put toward developing tools and methodologies to assess microgrid suitability in terms of cost or minimalization of life cycle costs, in which the formulation often assigns a cost to the unmet load. Multiple programs are dedicated to designing microgrids such as the Microgrid Design Toolkit (MDT) from Sandia National Laboratories, Hybrid Optimization model for electric Renewables (HOMER), and the System Advisor Model (SAM) developed by NREL [28]–[31]. The Distributed Energy Resources – Customer Adoption Model (DER-CAM) is an investment decision analysis tool. It is intended to optimize investments in a variety of DER under consideration based on objective function over time [32]. The Sandia Microgrid Design Toolkit (MDT) is similar to DER-CAM in capability. It allows the user to set element properties and specifications and then allow optimization based on multiple objective functions such as fuel used, time loads are met, cost, CO2, etc. [32].

Cost as an objective is the easiest and most justifiable decision driver, but the DOD's energy security interest is unusual in that national security is difficult to quantify in terms of a dollar figure. This makes many of the commercial microgrid cost tools unsuited for DOD application. Guidance documents for energy security in military microgrids “optimize the design through the maximization of the reliability of meeting the critical loads given a fixed investment or targeting a specific reliability value and minimizing a life cycle cost objective function with reliability as a constraint” [33]. Therefore, in the application of microgrids in DOD application, the “research from the Operations Research (OR) perspective performed on microgrids and electrical transmission systems sets objectives based on cost, resilience, and hardening against attack” [12].

Anderson’s research [19] attempts to address the relationship of resilience and cost in a way that is applicable to DOD installations, explored in the context of maintenance levels and life cycle cost analysis of energy (LCAE). Through his thesis, Anderson seeks to fill the gaps he found during his literature review. He determined that “no researchers have explored resilience of off-grid microgrids that therefore have disturbances that are not due to loss of power from the utility” and that very little research has been conducted of the relationship of resilience versus cost.

Hildebrand [34] takes a different approach to analyzing the relationship between cost and resilience by using the total life-cycle cost (LCC) of the designed microgrid. A more commonly used metric is levelized cost of energy (LCOE), which is often used to compare renewable energy resources. LCOE measures lifetime costs divided by energy production , which is “a useful metric to estimate cost and compare alternatives when the goal is to minimize cost over a system lifetime” [34]. The reason Hildebrand does not use LCOE is because “it is an inadequate metric if the goal is to maximize resilience or estimate the cost of resilience in a specific microgrid application” [34]. The reasoning traces back to the fundamental difference the concerns of civilian power suppliers and military microgrid power suppliers. Hildebrand uses Peterson’s ELMI as the resilience metric when comparing cost and resilience of microgrid architectures. He uses linear programming to determine the ELMI of each architecture using four different failure modes and develops a cost model for each architecture to provide the LCC. Regression analysis is then performed to determine the relationship between LCC and ELMI in order to “inform the design decisions for a naval installation microgrid” [34].

D. TRADE-OFFS

This report assesses existing research to determine effective microgrid design variations to allow base energy managers to easily determine which trade-offs best suit their installation requirements. Determining better design options requires an exercise in trade-offs including but not limited to design parameters such as sizing, capacity, load, electrical analysis, configuration, as well as reliability, procurement cost, life cycle costs, maximizing location, minimizing environmental factors, potential earnings, security, maximizing renewable resources, and of course resilience [12].

Table 3 is a matrix cataloging the existing microgrid design and evaluation tools reviewed by MSET and authors represented in the literature review. MSET divided the tool characteristics into five trade space categories: accessibility, economics, electrical architecture, "-ilities," and attributes. Each of the five categories were further divided into sub-categories to further specify the tool capability intention. Some of the tools listed are commercial software tools that can be acquired or accessed for a licensing fee or subscription cost, but limited access forced MSET to infer the capabilities from descriptions or reviews, these are indicated by triangles in the table.

Table 3. Trade Space Exploration - Available Microgrid Assessment Tools

	Source	Accessibility			Economics		Electrical Architecture							ilities			Attributes		
	Tool/Feature	Standard DOD Software	Open Source	MSET Access	Cost	Investment	Battery Sizing	PV Array	Other Renewable Resources	Power Flow Modeling	Evaluate Energy Storage	DG Sizing	Meeting Critical Load	Recoverability	Maintainability	Reliability	Mission Impact	Emmisions	Variable Time Scaling
NSETTI Tools	Chris Peterson		O	O										O		O	O		
	Bill Anderson	O	O	O		O							O	O	O	O			O
	Oriti Build	O	O	O						O			O						O
	Ruth Fish	O	O	O			O	O	O	O	O	O	O						
	Petros Siritoglou		O	O			O	O	O	O	O	O	O						
	Dan Beaton	O	O	O			O			O			O	O		O	O		
	Josh Hildebrand	O	O	O	O	O											O		
Commercial Software	HOMER		▲	▲	▲	▲	▲	▲	▲	▲	▲	▲			▲			▲	
	DER-CAM			O	O	O		O	O	O	O	O							
	XENDEE				▲	▲	▲	▲	▲	▲	▲	▲	▲					▲	▲
	NREL Reopt (Need to finish)				▲			▲	▲				▲						
	NREL REopt Lite			O	O	O	O				O	O	O						O
	MDT			▲	▲		▲	▲	▲	▲	▲	▲			▲	▲			▲
	Sandia ES-Select Tool			▲	▲		▲	▲	▲	▲	▲	▲							
	Power Analytics Paladin DesignBase						▲	▲	▲	▲	▲	▲	▲						

O Confirmed Reference
▲ Inferred Reference

Table 4. Explanation of Trade Space Categories. Adapted from [16], [21], [35].

Trade Space Categories	Trade Space Headers	Description
Accessibility	Standard DOD Software	Tool in question runs on standard DOD software
	Open Source	MSET had access to the source code and background information upon which the tool was built
	MSET Access	MSET had access to the tool in question during development of the MSET tool
Economics	Cost	Dollar per unit of power
	Investment	Validates the technical or financial performance of the microgrid over its expected lifetime
Electrical Architecture	Battery Sizing	Provides the number of batteries based on the user input battery type and rating (NSETTI tools). Provides a pattery size for the micgrogrid architecture (Commercial Tools)
	PV Array	Provides the number of PV panels based on the user input PV type and rating (NSETTI tools). Provides a PV size for the microgrid architecture (Commercial Tools)
	Other Renewable Resources	Set up for an energy generation source other than solar or DG
	Power Flow Modeling	Graphical output of power supplied over time
	Evaluate Energy Storage	Energy storage considered in the tool (i.e. chemical batteries)
	DG Sizing	Provides the number of DGs based on the user input DG type and rating (NSETTI tools). Provides a DG size for the microgrid architecture (Commercial Tools)
	Meeting Critical Load	Binary measure of the architecture's ability to meet the critical load demand
ilities	Recoverability	Engineering Recoverability by Li and Xi - "Recoverability is defined as the probability that a failed component or system recovers to perform the required function at given time."
	Maintenanibilty	Blanchard and Fabrycky - "Maintainability is that characteristic of design and installation that reflects the ease, accuracy, safety, and economy of performing maintenance actions."
	Reliability	The Department of the Navy's defines their terms in the Naval Facilities Engineering Command (NAVFAC) P-602 as: Reliability: the percentage of time energy delivery systems (utilities) can serve customers at acceptable regulatory standards. Reliability can be measured by the frequency and duration of service disruptions to customers.
Attributes	Mission Impact	Grab definition from Peterson
	Emmissions	Carbon Monoxide emissions
	Variable Time Scaling	The ability to change the time step within the model

MSET determined that accessibility carries the highest weight when assessing the usability of the tool. The sub-category "standard DOD software," indicates the tool can run on standard software programs available to the DOD. Another sub-category, MSET access, indicates that the team had access to a copy of the tool during development of the tool. The open-source sub-category indicates there was full access to the code or formulas upon which MSET could build. For initial tool assessment, MSET determined that tools that were good candidates must have all three accessibility features. Although several other tools had significantly more advanced capabilities, they were often expensive, specialized, and/or not open source making them unsuitable for the MSET project purposes.

The economics category consists of cost and investment attributes. Cost is the monetary value for a unit of power for a period. This is often a key metric in assessing the cost of power loss for commercial entities. Investment considers the return on investment for the purchase of a particular attribute in the microgrid. Investment is meant to validate the technical or financial performance of the microgrid over its expected lifetime.

The category Electrical Architecture covers EE design considerations of microgrid component performance. Each subcategory indicates if the toolset addressed the electrical design of a particular system type as listed. The matrix utilizes sub-category definitions primarily based off NSETTI tool functions because full access was unavailable for analysis of the understanding of the commercial tools.

The "-ilities" category covers reliability, recoverability, and maintainability. These are intended to identify the general nature of non-functional characteristics used to evaluate system performance addressed by a tool during MSET's assessment. These are intentionally broadly defined due to the known variation in each tool and are categorized in this manner to indicate the tool's intended coverage for potential future reference.

Finally, the attributes category covers mission impact, emissions, safety, and variable time scaling. The category is used as a catch all location for characteristics deemed important to note that lacking an overarching category. Most of the tools that fall under this category are commercial products on which MSET lacked visibility.

The exploration of the trade space between the major categories is important for effective analysis of stakeholder options. For the DOD, the product is national defense, which does not have an easily defined value [36]. The quantification of DOD energy resilience lacks standardization and remains open to interpretation, there is no one defined value of resilience [37]. The primary scope of the MSET effort is to integrate existing tools into a single streamlined interface for base energy managers. To this end, MSET intends to build off the research conducted by NSETTI participants, primarily Bill Anderson, Giovanna Oriti, and Josh Hildebrand.

III. METHODOLOGY

This chapter details the systems engineering process MSET utilized throughout this report. Chapter III.A provides a detailed description of the Incremental Commitment Spiral Model (ICSM) process and MSET's reasoning behind its application. Further discussion covers the stages of the ICSM, their various phases, and how they were tailored to meet the needs of this report. Chapter III.B addresses the risk management process followed by MSET throughout the development of the tool and the reasoning behind passing a phase gate.

A. ICSM SYSTEMS ENGINEERING PROCESS

MSET utilized the ICSM systems engineering process per Figure 12. ICSM's iterative nature provided greater flexibility throughout the development of the tool. It allowed MSET to ensure that each iteration of the process produced a functional prototype that satisfied the operational concept and the stakeholder before progressing to the next cycle. This was accomplished utilizing risk opportunity management with actual products. The spiral diagram of the ICSM process as applied by MSET is shown in Figure 12.

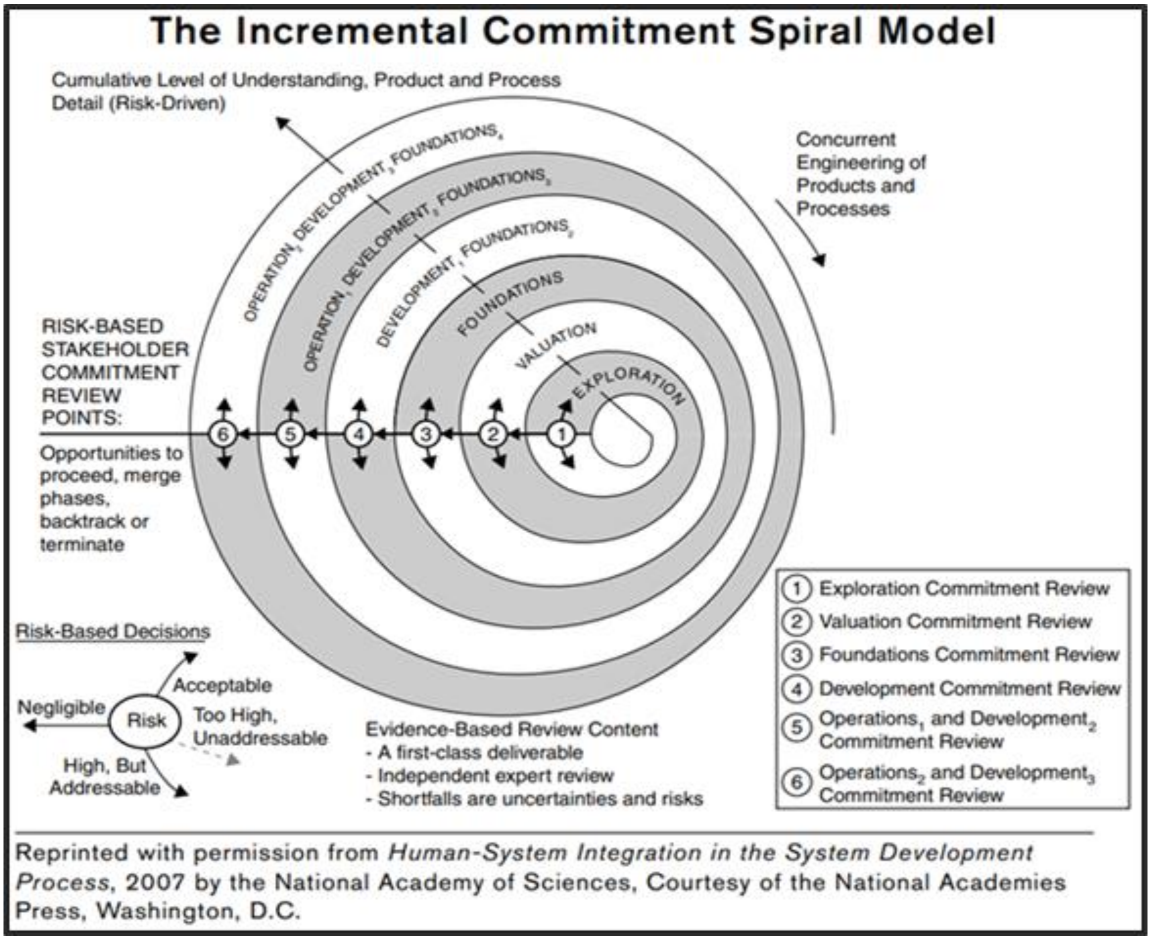


Figure 12. Incremental Commitment Spiral Model Tailored for the MSET process. Source: [36].

The ICSM process is broken down into activities in Figure 13 to cover the process life cycle from the exploration of concept through the operations and production phases with each phase culminating in a phase gate risk assessment. The phase gate passing criteria required the identification and evaluation of risk as acceptable prior to progressing to the next phase. If the risks were deemed high but addressable, then the project should remain in that phase. Too high, a non-addressable risk would indicate that the project needs to adjust priorities, scope, or to begin a new prototype iteration to restart the ICSM process cycle. Only an acceptable or negligible risk assessment will allow progression through the phase gate on to the next phase.

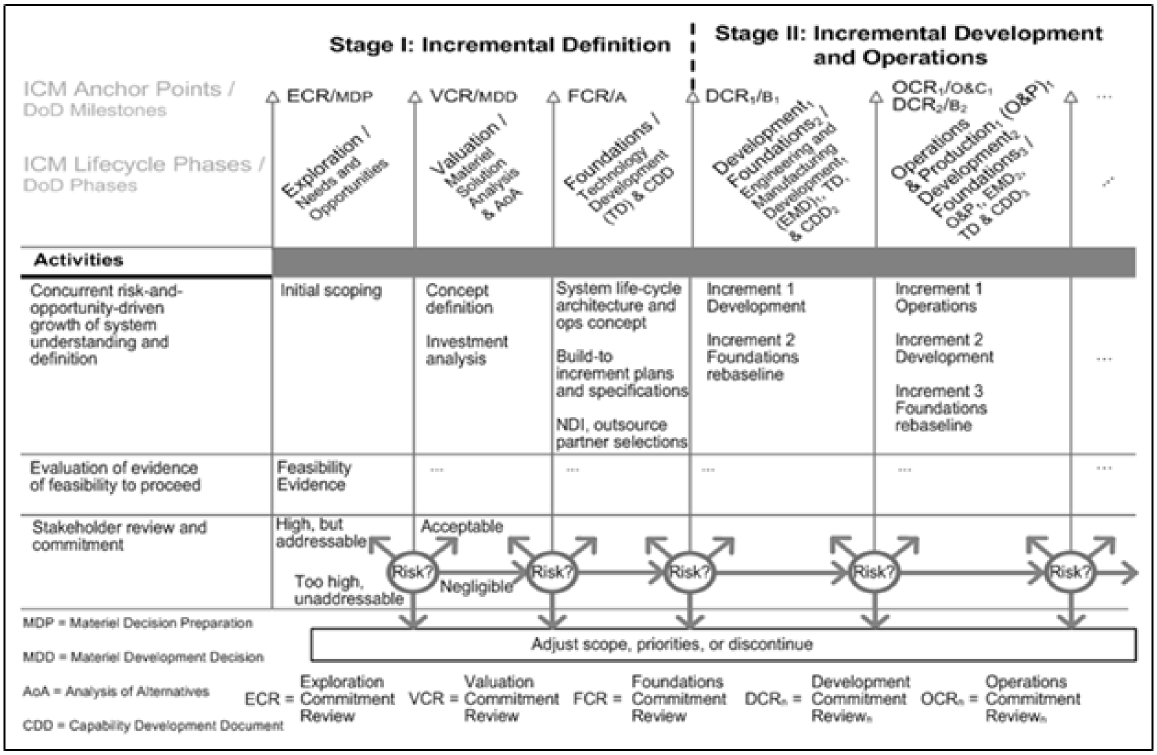


Figure 13. Incremental Commitment Life Cycle Progress Overview. Source: [38].

MSET utilized a tailored ICSM approach by combining the exploration and valuation phases; Boehm refers to this pattern as "Target Solutions Available." Chapter II.D covers the exploration and valuation phases in which MSET established scope boundaries by assessing microgrid toolsets currently available and using it to determine which tools were viable for MSET purposes. MSET performed a literature review at the outset which revealed several tools were already available. Since the purpose of this report was to take separate tools with different capabilities and integrate them into a single tool, as such, a combination of the exploration and valuation phase was determined to be the best approach, as shown in Figure 14. This allowed for concurrent identification of capability needs, constraints, opportunities, and alternative solution analyses and identification of desired options. When MSET began this technical effort, there were already several NSETTI tools in various stages of development with differing levels of maturity. As toolsets from William Anderson, Josh Hildebrand, and Dan Beaton, who were conducting their own work concurrently with MSET came available, MSET was able to integrate more functionality from their research into the MSET tool.

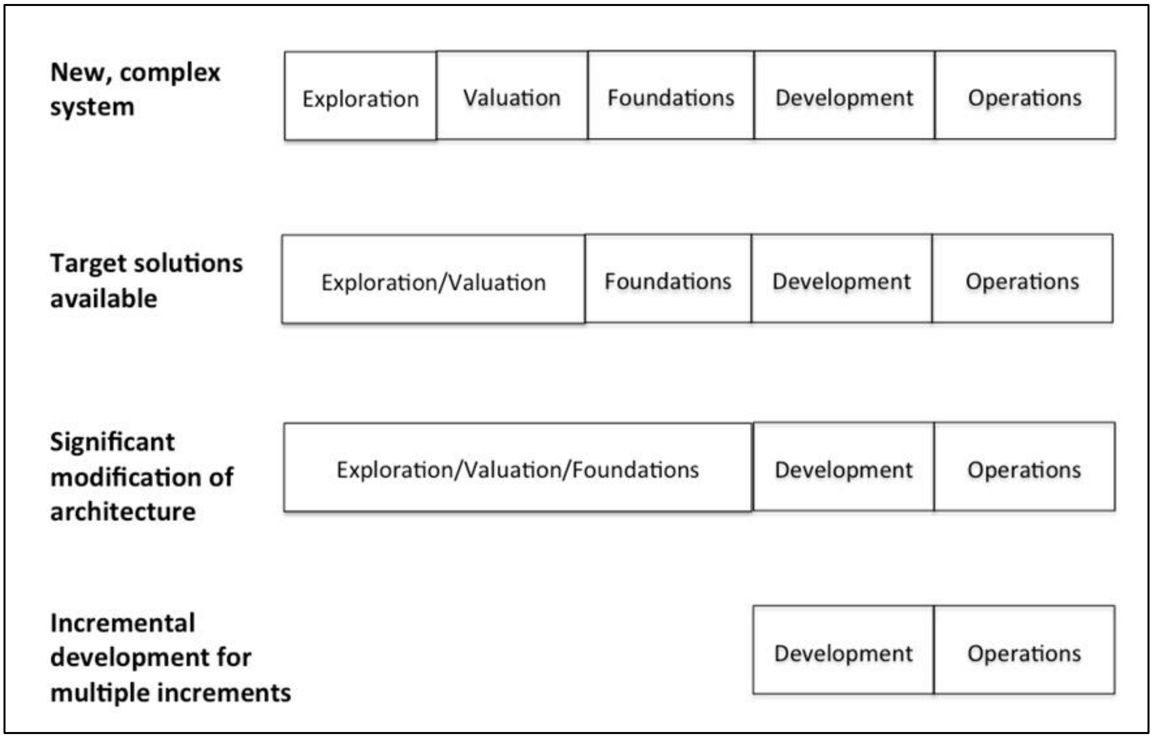


Figure 14. Breakdown of Different Process Options Based on Project Start Point. Source: [38].

Once past the Exploration/Valuation phase gate, the next step was the foundations phase. Along with ensuring technology readiness for needed capabilities, this phase activity also prioritizes features and requirements for development; monitors changes in needs, opportunities and risks; and updates risks and risk mitigation plans [38]. The foundations phase gate was assessed as low risk since this technical report was scoped to accept existing microgrid tools at their current maturity level.

The development phase produces an incremental development prototype and incremental foundations re-baseline. MSET continuously reassessed the capability and constraints of the individual toolsets when delving deeper into each. MSET scrutinized each feature to determine if it was worth keeping or if other tools should be reassessed for usability in contrast to initial planning. The MSET ICSM process activities end at development, specifically because the production and operation phase are for user release and use. Since this technical report focused on producing multiple iterations of the tool to bring it to the furthest integration development within the limited time frame, there was no attempt to proceed into the production or operation phase.

B. RISK MANAGEMENT PROCESS

The five-step risk management process outlined in the Department of Defense Risk, Issue, and Opportunity Management Guide for Defense Acquisition Programs [39] was used to manage programmatic risk, and is subsequently outlined in the following paragraphs. The same risk-opportunity fundamentals were also leveraged for the ICSM process. The first phase of the five-step process is the risk process planning which is intended to develop methods or processes to manage individual risks. Once the risk process planning phase was complete, MSET identified various risks that could affect the project, and determined the effects each risk could have on the overall success of the program during the analysis process. The estimation of likelihood that the risk will occur was assessed and once the possible foreseen risks were identified and analyzed, MSET developed a plan to mitigate the identified risks. In this step, MSET attempted to lower the probability of the risk occurrence while trying to lower the overall consequences of the risk. MSET applied this risk management process throughout the development of the tool and monitored all listed programmatic risks to determine if mitigation plans were working and/or if risks changed. If the changed risks were identified a significantly different, the risk was reassessed through the same methodology process [39].

The same five-step risk management process was leveraged for ICSM during the development of the tool. Since ICSM is a risk-based process, it was necessary to utilize the five-step risk process while determining when it was appropriate to move to the next phase. Risk-based decisions use evidence to assess feasibility risk and opportunity. The ICSM framework is based around the acknowledgement and management of uncertainty through risk and opportunities based on evidence-based decisions, phase gate milestones, and an incremental approach. MSET used the 5-step risk management process iteratively at each phase gate with a known deviation at the mitigation step. MSET assessed the risks and since the scope of the project was to primarily integrate existing tools without modification, the mitigation step was utilized to determine only if MSET could successfully integrate that parameter. For ICSM tool development risk, the mitigation focused more on whether a successful iteration was probable as opposed to lowering the risk of integration by suggesting a modification or a course change on the part of the previously developed toolsets.

IV. TOOL DEVELOPMENT

This chapter describes the development of the MSET tool. The tool was produced using existing EE and SE toolsets. The design of the tool follows the ICSM process, as outlined in Chapter III, resulting in a series of working prototypes. Each prototype is a spiral extension of the next, building on prior work based on evidence-based risk and opportunities discovered during the development cycle of each iteration. Throughout the development of the MSET tool, MSET's focus was to ensure the continued development of an operationally functional prototype that is easily understandable and usable by base energy managers to assess the mission impact of microgrid variable changes. During the development of the tool, MSET went through five iterations (Spirals) of the tool, see Figure 15 for summary.

	Summary	Timeline
Spiral 1	Power Flow Model baseline. Developed streamlined users tab for user required inputs, assessment outputs, relevant graphs.	~1 weeks
Spiral 2	Integration of Reslience model. Removal of wind turbines, modification of resilience model for functionality.	~3 weeks
Spiral 3	Modify resilience model, validate resilience model, incorporation of Resilience Cost model.	~2 weeks
Spiral 4	Integration of NPV Cost model, ELMI model build, resilience score testing and removal.	~3 weeks
Spiral 5	Trade-off analysis tab, inteface cleanup.	~2 weeks

Figure 15. Spiral Summary

A. FIRST SPIRAL

This section describes the first integration effort for the MSET tool. The Foundations Phase of the first iteration intended to ensure that MSET considered the system life cycle concept and CONOPS. To this end, MSET generated an input/output diagram, shown in Figure 16, to illustrate and assist with comprehension of the existing microgrid simulation tools.

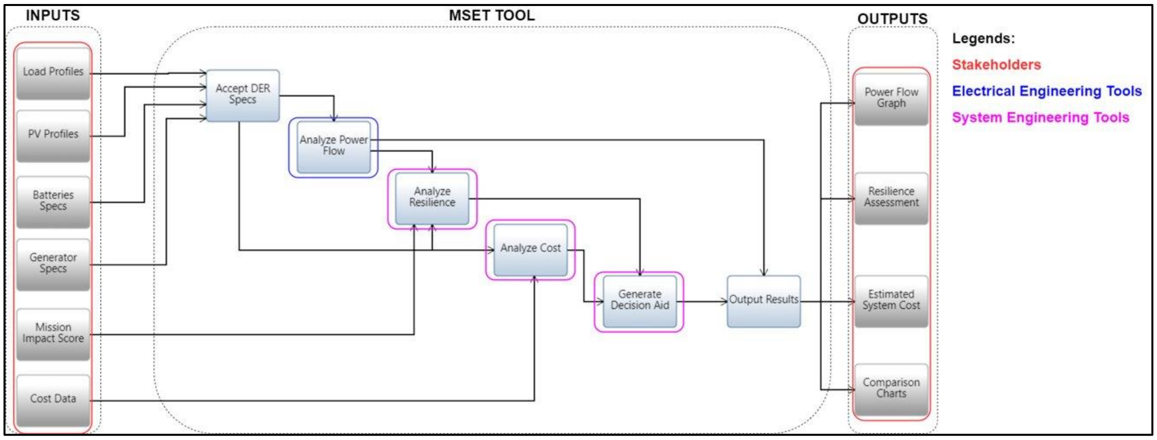


Figure 16. MSET Tool Input / Output Diagram

In order to determine the acceptable risk of proceeding into the Development Phase, MSET needed to fully understand the inputs and outputs used by the known available models. The interface document was used to prioritize the down select for tools that were considered the most relevant to the user needs and most suitable for integration with each other.

MSET chose to utilize Giovanna Oriti's [40] power flow model as the baseline microgrid tool for MSET integration. The power flow model requires a set of background information for proper functionality. The first task MSET took on was to divide all the data and user inputs into separate tabs. MSET effectively created the "User Interface" tab and a "Data" tab. The Data tab contains user definable stock data necessary for model reference in Spiral 1, which includes a table of known solar irradiance characteristics per month as well as the microgrid load demand requirements, depicted in Figure 21. To account for PV output, public data provided tailored solar characteristics for a specific location.

Table 5. Data Tab Regional Solar Characteristics

PV Characteristics Spain		
Months	PV Output (MW)	PV Width
Jan	0.0311	0.42
Feb	0.0343	0.45
Mar	0.03675	0.5
Apr	0.03915	0.54
May	0.03955	0.59
Jun	0.04035	0.59
July	0.03995	0.59
Aug	0.3955	0.59
Sep	0.0386	0.5
Oct	0.0358	0.46
Nov	0.03285	0.42
Dec	0.0307	0.42

Table 5 outlines both the PV output (energy) and PV width (percentage of time throughout one day PVs will produce). The "Data" tab also includes load demand data, which must be provided in four-minute time steps over a 14-day period for each month of the year. The load data used during development is notional data based off a sample building to avoid restricted distribution. This data can be seen in Table 6.

Table 6. Data Tab Load Demand

	A	B	C	D	E	F	G	H	I	J	K	L
1	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2	0.172728	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173
3	0.172728	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173
4	0.177025	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177
5	0.177025	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177
6	0.177025	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177
7	0.177025	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177
8	0.180462	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
9	0.180462	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
10	0.180462	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
11	0.180462	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
12	0.172728	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173
13	0.172728	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173
14	0.172728	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173
15	0.172728	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173	0.173
16	0.162416	0.162	0.162	0.162	0.162	0.162	0.162	0.162	0.162	0.162	0.162	0.162

Each cell is an open-source load demand at four-minute time steps in each month and spans 14-days. This data is used to determine whether the microgrid can meet the load demand for any particular month. The monthly load demand and PV ratings make up most of the data tab and necessary information to analyze the resilience of a microgrid.

The user inputs the solar characteristics and base load requirements for their microgrid consideration in the “Data” tab, while the inputs that the users more frequently interact with were consolidated to the “User Interface” tab. In this specific case, the user can select the month of interest. The portions of the Power Flow model that performs the power balance calculations and generates power flow graphs was implemented on the “Power Flow” tab, which extracts the necessary inputs from the “User Interface” tab. Once the month is selected by the user, that month’s load data is extracted from the “Data” tab and populates the load column in the “Power Flow” tab and sets the amount of expected solar irradiance available to the PV. The solar irradiance by month is important because it considers the changes in the amount of sunlight throughout the year, which will affect the PV’s performances.

In addition to the “User Interface” and the “Data” tabs, the “Power Flow” tab shows the power flow model and a clear graphic of how three different DERs (DG, PV, and Battery Energy Storage System (BESS)) interact and how they support the demanded load. The energy management method uses the BESS, the purple line in Figure 17, to pick up the load when the outside utility grid connection fails at night. Figure 17 shows the battery state of charge (SOC) for the duration of the power flow model.

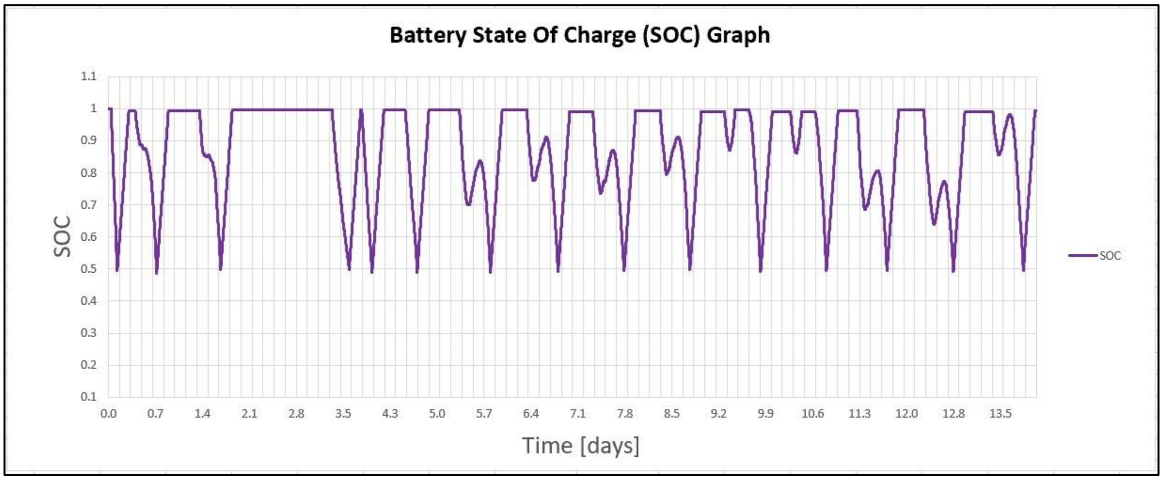


Figure 17. Power Flow Model Battery State of Charge

The state of battery charge for this particular run never drops below 50%, meaning the PV or DG were always able to take over by the time 50% of the battery charge had been depleted. Again, the duration is 14 days, which is in line with the load data being pulled from the data tab. Where Figure 17 shows information on the battery, other graphs portray the relationship of activities between two or all three of the energy producing sources show in Figure 18.

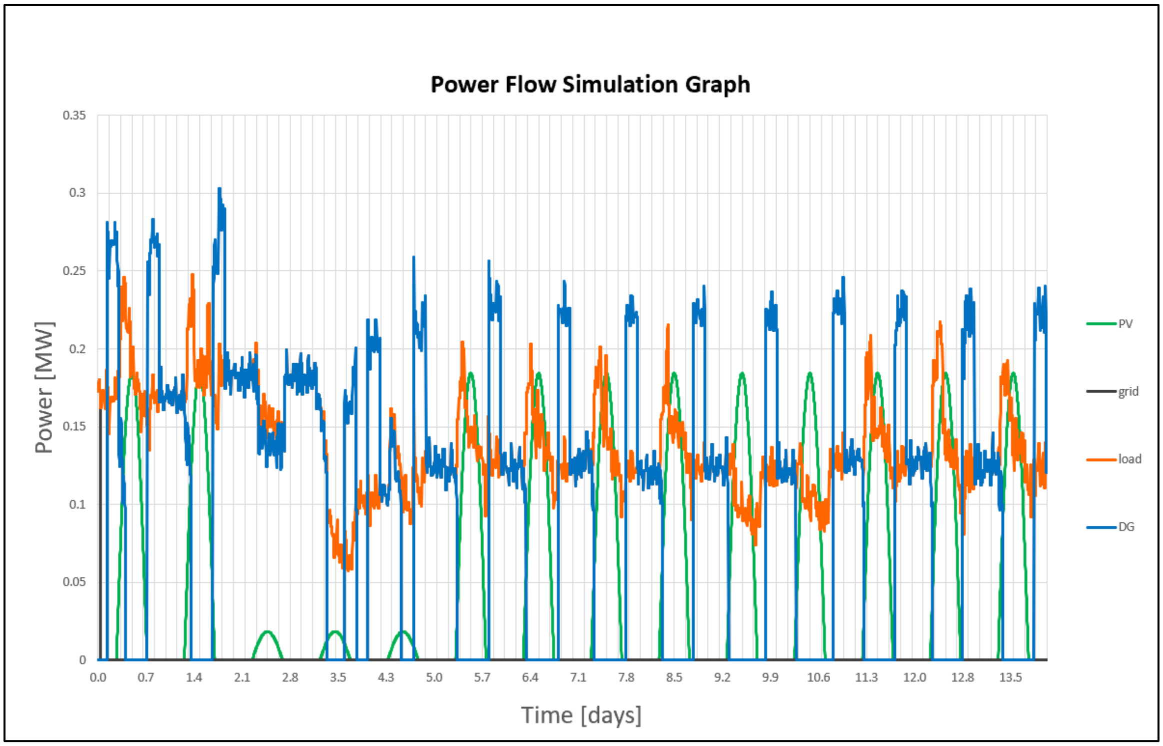


Figure 18. Power Flow Output Showing Interaction Between DG, PV, and Load

After the first 30 minutes of the simulation, the DG (blue line in Figure 18) starts up because the BESS has reached a 50% SOC. At this point, the DG carries the load as well as charges the BESS. The DG and PV activity can be seen in Figure 18. When the sun comes up, the PV, shown by the green line in Figure 18, starts producing power, and in conjunction with the BESS, supplies the load demand during the day, allowing the DG to shut down. Once the sun goes down and the PV no longer supplies power, the DG and the BESS cycle through the night in order to reduce fuel requirements. Figure 19 shows all required user inputs needed to output the power flow graphic.

Load scaling	1				hrs	min
PV rating	0.3	MW		grid off at	1	60
Month	Dec	0		genset on	1.5	90
BESS rating	0.8	MWh		sun is less	2	(days)
BESS upper limit	0.99			sun returns	5	(days)
BESS rate of charge	0.1			sunlight	0.1	
BESS min SOC	0.5			batt efficiency	0.95	
DG rating	0.32	MW				
DG min load	0.096	MW				

Figure 19. Original Power Flow Model Inputs

The user is not required to change the “sun is less,” “sun returns,” and “sunlight” values as these are specific to simulating a cloudy day. If the user desires a sunny day condition, the user may leave these “sun” values blank. The original power flow model was not modified in any way and a more detailed explanation of the functionality of the model can be found in [40].

MSET noted that the inputs could be organized to be more user-friendly by condensing user input information together and categorizing them by DER type, grouping reference information separately, and showing output data in an area of its own. The “User Interface” tab allowed for groupings of the more common input changes for this and future input features. As additional models were integrated into the MSET tool, the input sheet was expected to expand and be reorganized to maximize the interface for intuition.

The power flow model output remained on the “User Interface” tab to clearly indicate how each DER contributes to meeting the load demand. During this Development Phase, MSET discovered a coding issue with the DG power output in column G of the “Power Flow” tab. Testing revealed that some of the power flow-generated DG outputs in the output graphs were greater than the user input DG ratings, which should not be possible. The microgrid model should not be able to produce more than the input specification of its DERs. This flaw was due to the DG being coded to always supply the necessary power to carry the critical load, even if it required power beyond the capacity of the DG. After numerous unsuccessful attempts to fix the coding, MSET worked around this limitation of the model by plotting the input DG rating directly on the power flow graph shown in Figure

20. The black line on the graph allows the user to visually identify when the DG provides more power than for what it is rated.

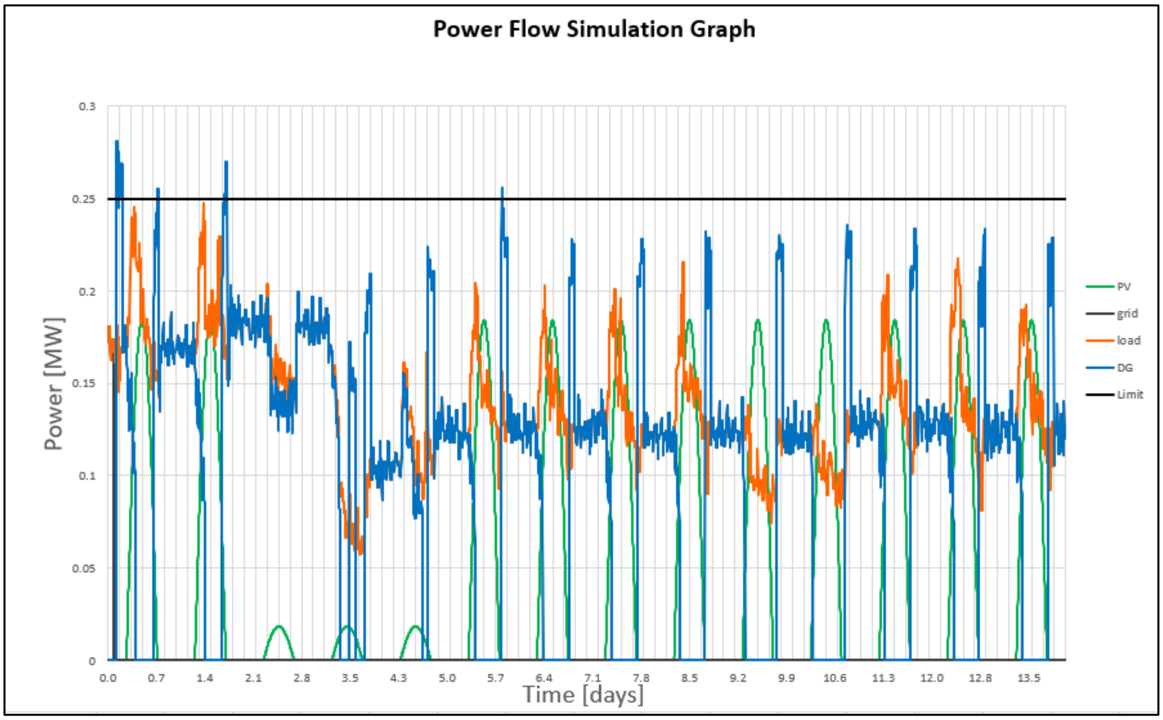


Figure 20. Power Flow Graph Presented in the "User Inputs" Tab of the MSET Tool

Figure 20 shows four instances where the blue DG output line crosses the black DG rating line, indicating that the DG output is not possible. To avoid instances where visual identification was not clear, a tabular dimension with a text "Yes / No," shown in Figure 21, was provided to indicate the possibility of the DG output.

OUTPUT	
DG output possible?	**NO**

Figure 21. DG Output Possible from the "User Interface" Tab

If this field is "NO," the user is immediately able to identify the error and change the DG power ratings entered before moving on to further analysis. Having a simple yes/no answer, relieves the user from having to interpret the graph. With these modifications made, MSET moved onto testing the integrated model.

Toward the end of this spiral, testing was conducted to ensure that no issues were created during the integration of the user interface tab and the power flow model. Test cases were created to ensure the MSET tool continued to output the same results as those of the original tool. The three test cases for spiral 1 are shown in Table 7.

Table 7. Spiral 1 Test Cases

Purpose	**Month**	**PV Rating (MW)**	**Expected Results**	**Notes**
Does changing the user input change the power flow parameters?	December	0.1	0.0614	Correct Output
Purpose	**DG Rating (MW)**	**Maximum Load (MW)**	**Expected Results**	**Notes**
Does the DG graph drop as the DG rating decreases?	0.15	N/A	DG Graph should show a decrease	Incorrect Output
Does the model detect if the DG output is impossible?	0.2	0.247	Model detected the output was impossible	Correct Output

The first test case was conducted to ensure that the power flow graphics changed in accordance with the user inputs on the "User Interface" tab, which meant the input parameters on the "User Interface" tab were linked properly to the required inputs in the "Power Flow" tab. The second test case was driven by observations made while putting different DG ratings in the inputs. The observation was that the blue DG line in the power flow graph did not hit an upper limit if an undersized DG was used. MSET's workaround for this problem is described in the previous paragraph and the failed test was considered acceptable with the mitigation in place. The final test case tests the coding of the "DG output possible?" output. As shown in Table 7, a DG rating of 0.2 MW was input and the maximum value of the DG output in the "Power Flow" tab was 0.247. The DG output is not physically possible so an answer of "NO" was output representing correct tool behavior. With the test cases showing that the integration was successful, MSET turned to adding greater capability to the model in the form of a resilience calculation function.

B. SECOND SPIRAL

MSET's second iteration intended to bring simplified components of Anderson's model and link it with the MSET tool. Adding the new components immediately expanded the "User Interface" output table with a numerical score display, between 0 and 1, of the microgrid configuration's resilience, invulnerability, and recovery. Most of the second spiral was dedicated to adding the additional inputs required to make the resilience model operate. The first point of interaction between the current MSET tool and Anderson's resilience model was the load profile, which is linked directly from the "Power Flow" tab. The load data was pulled selectively per hour because the "Power Flow" tab required 4-minute timesteps while Anderson's model required 1-hour time steps. The second point of interaction is the power rating of each DER asset, which are transferred directly from the "User Interface" tab. Risks encountered during this spiral forced MSET to adjust priorities and scope to achieve a successful working model that incorporated the resilience analysis function. The first trial was discontinued after determination of unacceptable risk to the project schedule, but the second redirected trial led to a successful integration.

1. Second Spiral – Trial 1

In the first trial, MSET wanted to incorporate resilience analysis. MSET learned through the first spiral that merging complex models in their entirety caused difficulty with tool integration. It is worth noting that Anderson's model has higher granularity than the power flow simulation and incorporates wind turbines as part of the microgrid configuration. Therefore, for the second spiral, MSET attempted to simplify Anderson's resilience model to the directly relevant functions and components, focusing only on the outputs: invulnerability, recovery, and their relevance to resilience.

MSET gathered preliminary microgrid data in preparation for the case study using real world data from a naval installation that consisted of DGs, PVs, batteries, and explicitly did not include wind turbines. Since the power flow model did not take wind turbines into consideration, and knowing the future case study lacked wind turbines, MSET predicted that the model could be further simplified by removing the wind turbine feature from the resilience model. However, the high level of coupling throughout the model made removing a single component extremely difficult, incurring significant risk. After the wind turbines were removed, testing resulted in numerous malfunctions due to the removed components and its coded interactions with formulas throughout Anderson's model. Several attempts to reorganize and remove wind turbines all continued to result in similar errors. The process of combing through the entire model to remove the wind turbine component completely was taking excessive amounts of time. MSET evaluated the risk of continuing as too high and, as a result, MSET reentered the second spiral with Anderson's original resilience model without any modification.

2. Second Spiral – Trial 2

After MSET determined the scale of risk associated with removing the wind turbines, MSET elected to leave the wind turbines in place and manually ignore them by setting the power ratings to "0" and the control authority variable, a built-in feature of Anderson's model, to "0" (Not used). Setting the wind turbines to zero simulated their absence without disrupting the other aspects of the model.

The MSET tool in this trial was based on a single architecture consisting of a single DER unit of each type, whereas Anderson's resilience model permitted various architecture options allowing multiple units of DERs. Although having multiple DERs is a more accurate approach, only one of each DER component was considered in this spiral. Setting the remaining DER to zero allowed the components to act as placeholders to leave room for potential future expansion of the tool. The final step in the second spiral was to link the primary outputs of invulnerability, recoverability, and resilience to the output section of the "User Interface" tab which would provide a resilience assessment of the DER architecture and chosen component ratings to the user.

Table 8 catalogs the tests performed at the end of the second spiral. These tests were performed to ensure the integration of the resilience tool once again into the MSET tool did not cause any unexpected behavior.

Table 8. Spiral 2 Test Cases

Purpose	Maintenance Level	Disruptive Event	Expected Results	Notes
Does changing the user input change the power flow parameters?	Medium	Hurricane	Changing maintenance level and disruptive event changed the parameters	Correct Output
Purpose	**DG Rating (MW)**	**Maintenance Level**	**Expected Results**	**Notes**
When removing the wind turbine, does the resilience score increase when the DG rating & maintenance level increase?	0.3 → 0.6	None → Medium	Resilience score is increased	Incorrect Output
When setting the wind turbine rating = 0, does resilience score increase then the DG rating & maintenance level increase?	0.3 → 0.6	None → Medium	Resilience score is increased	Correct Output
Does the resilience output update correctly on the "User Interface" Tab?	0.3 → 0.6	None → Medium	"User Interface" Tab reflects updates to resilience score	Correct Output

The first test case was specific to the power flow in Anderson's tool. Changing the maintenance level and disruptive event in the "User Interface" tab changes those parameters in the "Resilience Model" tab, representing a correct interface between the two MSET tool tabs. The second test case shows why MSET decided to set the wind turbine power ratings to zero instead of trying to remove them. When MSET tried removing the wind turbines from the model, the model output was not as expected. The third test case was the same as the second test case but had the desired output. When the DG rating was increased from 0.3 MW to 0.6 MW and the maintenance level was increased from none to medium, the resilience score increased. Finally, the fourth test case verified that the change in the resilience score in the "Resilience Model" tab was linked properly to the "User Interface" tab.

C. THIRD SPIRAL

After the successful integration of the second spiral, MSET focused on adding more capability by trying to slightly modify the resilience model instead of incorporating another model. The first trial effort involved utilizing Microsoft Excel's built-in solver function to determine an ideal set of DER power ratings based on achieving a higher resilience score. The second trial was intended to validate the resilience model by observing an ideal resilience score of 1.00. These first two trials both failed that ultimately lead to the final trial which attempted the integration of Anderson's cost model into the overall MSET tool.

1. Third Spiral – Trial 1

Due to the complexity of Anderson's tool, MSET considered the tool as two separate functions, the resilience model and the cost model, each of which were transferred to the MSET tool in a tab of their own. Initial integration attempted to determine optimal DER power ratings by using the Microsoft Excel's built-in solver. Based on the user inputs from earlier development spirals, a resilience score was calculated using Anderson's methodology which was incorporated in the "Resilience Model" tab. Equation 4.1 was used to calculate an aggregate resilience score by weighing invulnerability and recovery with an alpha coefficient.

$$\xi = \alpha \; invulnerability + (1-\alpha) \; recovery \tag{4.1}$$

The alpha coefficient can vary depending on the geographic area of the microgrid, but the original resilience model was built with an alpha coefficient of 0.5, meaning the resilience score was affected equally by the invulnerability and the recovery of the microgrid. The invulnerability term in Equation 4.1 is defined as the ratio of the stabilized microgrid capacity after a disruptive event, divided by the microgrid power capacity prior to the disturbance. Invulnerability is shown mathematically in Equation 4.2.

$$invulnerability = \frac{P_{t_s}}{P_{t_d}} \tag{4.2}$$

In Equation 4.2, P_{ts} the stabilized power capacity and P_{td} is the pre-disturbance power capacity [19]. The recovery term is the ratio of the area bounded between the demand and post-disturbance generation curve divided by the demand curve, shown mathematically in Equation 4.3, where D_t is the demand at time t, and G_t is the post-disturbance power generation at time t [19].

$$recovery = 1 - \frac{\sum_{t=t_d}^{t_{fr}} D_t - G_t}{\sum_{t=t_d}^{t_{fr}} D_t} \tag{4.3}$$

The addition of the solver was meant to determine the ideal combination of the power ratings of DG, PV, and battery for the maximum resilience score. Initial constraints were set such that the new resilience score would be greater than the current score and less than 1, with invulnerability and recovery scores of less than 1. Different test cases were executed to validate the newly implemented capability. The expected result was that the PV, DG, and battery power ratings would change, but instead, the solver results revealed enormous values for PV and minimum (even negative) values for the DG and battery ratings. To adjust for this issue, a constraint was added to ensure the resultant DER power ratings were values greater than zero with the hopes that the load would be spread between the different DERs. Increasing the number of constraints resulted in the solver being unable to meet the constraints or again, only change a single variable instead of balancing the three DER options. The constraint on the resilience score was opened up to limit the possible results to be greater than 0.6 but less than 1.0, and the constraints on the DERs were adjusted to require minimum values for each DER in order to ensure each was used. Yet again, the solver either generated errors or was unable to meet the constraints during most attempts. The times the solver was able to generate an acceptable combination of DER ratings with a high resilience score, the configuration was unable to supply the required load during the periods of darkness. After considerable effort, MSET determined that utilizing solver in this way was too risky. The effort was halted because of the extended time spent investigating this and that MSET was increasingly drawn into adjusting the invulnerability calculation in Anderson’s model, both of which were clear deviations from the original scope of the project.

2. Third Spiral – Trial 2

Frustrations with the previous solver trial drew MSET to test the MSET tool without a disruption event to observe an ideal case that would result in a resilience score of 1.0. MSET executed a scenario without a disruptive event, but the model behaved in an unexpected manner. The invulnerability appeared to be driven by the minimum load demand as the logic for determining P_{ts} would find the minimum microgrid capacity. Without a disruption event, the resilience model resulted in DER power ratings that consistently met the minimum demand over the two-week period; however, there was no stabilized power to use in the invulnerability calculation presented in Equation 4.2. Likewise, without post-disturbance power generation for Equation 4.3, there was no way to calculate recoverability.

Reliability and resilience definitions are based on exclusively post-disturbance behavior and therefore was impossible to set up or verify the model prior to a disturbance to observe an ideal resilience score of 1.0. MSET initially considered this an error and spent considerable time investigating the integration of the model and then searching for an error in the original model. After several consultations with the model's author, MSET realized we had become fixated on an impossibility, and a resilience score was reliant on a disturbance event. "After a HILP disturbance we would never expect this situation wherein the demand drops below the degraded power capacity immediately following the disturbance" [41]. MSET concluded that our interpretation of the invulnerability equation caused the misunderstanding and a resilience score of a normal operating microgrid cannot be measured since an undisturbed microgrid's invulnerability and recovery cannot be measured.

3. Third Spiral – Trial 3

After the earlier false starts and reviewing the project scope, MSET turned to the cost portion of Anderson's model, which was incorporated into the MSET tool as the "Cost Model (NPV)" tab. Anderson's cost model considers cost metrics in terms of life cycle cost of energy demand (LCOED), life cycle cost analysis of energy (LCAE), and life cycle cost analysis (LCA). Further information about these metrics can be found in Anderson's thesis [19]. These cost metrics were calculated through investment cost, maintenance level, and vendor's operation and maintenance (O&M) costs. Investment cost and the O&M costs are fixed for each DER asset, where the maintenance costs vary based on the selected maintenance level. Maintenance costs increase as the level of maintenance increases per methodology defined in Anderson's thesis [19].

Investment and O&M costs combined with the discount rate, also known as the weighted average cost of capital (WACC), were used to calculate the net present value (NPV) at the end of a 10-year period. Anderson had determined that doubling the recommended amount of maintenance was not a good return on investment, so three maintenance levels: none, low, and medium were chosen to illustrate the range of O&M cost options. Medium maintenance is set as the vendor's recommended annual maintenance, represented as J_{yi} in Figure 22. A low maintenance level is set at a 22% reduction of the vendor's recommended O&M costs, and a maintenance level of "none" indicates that no maintenance is performed, nor costs generated. Figure 22 shows how DER O&M costs (M_{yi}) for specific maintenance levels are calculated annually [19].

The pseudocode for determing M_{yi} follows:

```
IF maintenance level is medium
     THEN
            M_yi^medium = J_yi
     IF maintenance level is low
          THEN
                 M_yi^low = 0.22J_yi
          ELSE
                 M_yi^none = 0
     ENDIF

ENDIF
```

Figure 22. Maintenance Cost Calculation Using Vendor's Recommended O&M Cost. Source: [19].

The maintenance costs of each DER are assumed to be constant through the ten-year period. Maintenance costs here are simple because of the single architecture nature of the MSET tool. Cost model calculations were separated into the MSET "Cost Model (NPV)" tab, and additional inputs were added to the "User Interface" tab to allow the users to select the maintenance level and the discount rate. The validation and verification of Anderson's cost model was straightforward. Tests were performed to ensure MSET and the cost model output values were identical, given the same input values to ensure the integration did not interfere with the cost model functionality. Table 9 shows examples of test cases that were performed during the third spiral.

Table 9. Spiral 3 Test Cases

Purpose	Maintenance Level	DER Rating		Expected Results	Notes
Does the LCOE cost metric change as the maintenance and DER rating increase?	None → Medium	Increase		LCOE cost metric increase and reflected in the “User Interface” Tab	Correct Output
Does the resilience score increase as the maintenance level increase?	None → Medium	No Change		Resilience score increase	Correct Output
Purpose	**DG Rating**	**PV Rating**	**BESS Rating**	**Expected Results**	**Notes**
Does the resilience go up as the DG power ratings go up?	Increase	No Change	No change	Resilience score increase	Correct Output

At the end of Spiral 3, Anderson’s [19] resilience model and cost model had been integrated into the MSET tool. Test cases were able to observe expected relationships—as DER ratings increased; costs (LCOED) also increased because larger components had to be purchased. The test case with unchanged DER power ratings, but increased maintenance levels, was also run through a Monte Carlo simulation at 2,000 iterations, and the resilience score was observed to increase as expected. Finally, as the DG rating was increased, the resilience increased, which is the proper behavior. At this time, no other DERs were adjusted to see if cost or resilience increased because the number of iterations required to smooth out the random distribution within the resilience model was prohibitive to in depth testing, which the team would later realize was a mistake. Now MSET was complete with the third spiral, and we turned our sights to adding more capability to the MSET tool.

D. FOURTH SPIRAL

During the development of the MSET tool, two other microgrid evaluation models were in parallel development: Hildebrand’s [34] NPV cost model and Beaton’s [42] ESS resilience model Hildebrand’s NPV cost model focused on the lifetime cost and resilience of a microgrid system while Beaton’s ESS resilience model focused on resilience improvement through changing BESS architecture and power ratings. Initially, the MSET tool accepted data inputs for a single critical load, where the ESS resilience model required a detailed breakdown of individual loads that the microgrid would support. The MSET tool established its assessment early on for a single architecture in which the integration of the

ESS resilience model would be a greater risk because of its significant input deviations from the existing MSET tool.

Hildebrand's NPV cost model was the best fit for the next development iteration due to the more comparable assessment methodologies, but modifications were necessary to ensure proper conversion between the NPV cost tool and the MSET tool. The previous iterations referenced PV in terms of the power rating provided by the user on the "User Interface" tab. The NPV cost model used the user-input power rating and generated the cost of a PV system based on the area of the solar panels. The way PV was input and calculated throughout the MSET tool became consistent and condensed by converting the power rating of the PV to the solar panel area (m^2) using Equation 4.4 and 4.5 in the NPV cost model tab [43].

$$Total\ Power\ Output = Total\ Area \times Solar\ Irradiance \times Conversion\ Efficiency \qquad (4.4)$$

$$Total\ Area = \frac{Total\ Power\ Output}{(Total\ Power\ Ouput \times Conversion\ Efficiency)} \qquad (4.5)$$

The NPV cost model quantifies the cost of resilience in the net present value of the microgrid over ten years. MSET's incremental approach incorporated the NPV calculation to explore the cost quantitative portion for our user inputs separate from the resilience. The NPV model required the use of MATLAB to determine the ELMI value. MSET decided to remove the ELMI database from Hildebrand's tool that utilized MATLAB and replaced it with an "ELMI" tab that utilized Peterson's methodology with the resilience model to generate the ELMI of the user-defined microgrid.

Hildebrand assembled cost tables for each of the DERs based on investment and O&M costs across a range of power ratings. These tables were derived from numerous sources including generator sales representatives, FY21 Defense Logistics Agency (DLA) fuel cost standards, and representative models of ESS and PV systems. The data used to construct cost builds for each of the DERs are expected to change over time. These cost tables were reorganized and collected in the "Data" tab of the MSET tool. The NPV cost calculation was implemented in the "Cost Model (NPV)" tab of the MSET tool. This calculation integrated the inputs from the "User Interface" tab and the "Resilience Model" tab using the Excel NPV function [44].

In addition to the cost calculations, the battery efficiencies were observed utilizing Oriti's and Anderson's model. Oriti's and Anderson's models allowed for any battery efficiency to be used; however, Hildebrand's cost model had the limitation of estimating costs of an efficiency of 0.80 and 0.95. MSET modified the tool to limit battery efficiency options to that available in the cost data provided based on the ESS cost table. The input for the battery efficiency was a dropdown menu with two options of 0.80 and 0.95 battery efficiency, and the DER ratings were rounded up to the next closes rating/cost for NPV purposes only. Once the fix was implemented, MSET performed numerous tests to ensure the investment cost changes were responding correctly to changes in battery efficiency and power rating, per Table 10. Expected values were defined prior to testing, and all results matched expectations.

Table 10. Spiral 4 Test Cases for Battery Cost

Purpose	Battery Rating (MWh)	Battery Efficiency	Expected Results	Notes
Does investment cost change with changes in battery capacity?	0.9	0.8	-$214,678	Correct Output
Does investment cost change with changes in battery capacity?	1	0.8	-$214,678	Correct Output
Does investment cost change with changes in battery capacity?	1.1	0.8	-$429,356	Correct Output
Does investment cost change with changes in battery capacity?	2.1	0.8	-$644,034	Correct Output
Does investment cost change with changes in battery efficiency?	0.9	0.95	-$1,034,280	Correct Output
Does investment cost change with changes in battery efficiency?	1	0.95	-$1,034,280	Correct Output
Does investment cost change with changes in battery efficiency?	1.1	0.95	-$2,068,560	Correct Output
Does investment cost change with changes in battery efficiency?	2.1	0.95	-$3,102,840	Correct Output

The original NPV model was designed to generate the NPVs for multiple DER rating combinations to find the most efficient and affordable solution to increase microgrid resilience. The MSET tool considers the resilience of a single set of DER ratings at a time. MSET assessed that the NPV calculation methodology was the most compatible with

Hildebrand's work. The NPV calculation assumed the vendor recommended O&M costs for each of the DERs, which meant that all costs were defined at the medium level of maintenance used in the "Cost Model (NPV)" tab. During the integration of the NPV calculation, MSET ensured to account for different levels of maintenance cost by incorporating Anderson's maintenance level methodology, as seen in Figure 21 to ensure that the user selection of maintenance level in the "User Interface" tab was reflected in the NPV.

The NPV cost model evaluates resilience using ELMI in correlation with NPV costs. The team created an "ELMI" tab to correlate overall resilience with the "Resilience Model" tab, which allowed the comparison of the similarities between ELMI and NPV versus the resilience score and NPV. If the resilience metrics proved comparable, MSET considered ELMI the more subjective metric, so the resilience score was expected to become the dominant resilience metric.

The NPV cost model incorporates resilience through the ELMI, as the "total impact of disruption events over the expected lifetime of the system" [12]. The ELMI is a numerical measure of the system resilience when experiencing a power disruption event through expected environmental and non-environmental threats and influence [12]. The ELMI value is not independently useful, but its value lies in comparison, allowing the evaluation of resilience in relation to different DER ratings. A lower ELMI value comparatively implies better resilience. ELMI is calculated using mission impact (MI) and mission impact over the scenario (M_s). The MI is defined as "a measure of the base commander's preference for completion of a particular mission" [12]. According to Peterson, the MI is a subjective value between the range of 0–200, where 0 is the minimal priority for the base commander while 200 is the highest priority. For the MSET tool, a middling MI value of 100 was chosen to run the numerous iterations of the tool. Similarly, M_s is just the mean MI over all Monte Carlo simulations for that specific event scenario.

Peterson's resilience used M_s which was calculated for hurricanes, wildfires, earthquakes and cyber-attack scenarios by averaging the number of failures throughout the simulation using the equation below [12].

$$M_s = \sum_{t=1}^{T} MI \tag{4.6}$$

Once M_s was established for each event scenario, the ELMI, as discussed in Peterson's thesis [12], was determined by summing the M_s values for each of the four events:

$$ELMI \equiv \sum_{s \in S} Pr(S = s)\, M_s \tag{4.7}$$

Due to the stochastic nature of the resilience model, a certain number of iterations are necessary to get to the most accurate answer. The number of iterations is directly proportional to the tool runtime, and the team conducted a design of experiment (DOE) to recommend an iteration number that can balance accuracy and speed. Monte Carlo simulations were run with 18 different number of iterations between 500 and 7,000. Each run resulted in a unique ELMI value for each impacted scenario due to the stochastic behavior of the resilience model. Figure 23 illustrates the M_s values and ELMI scores resulting from the varying iteration runs. The M_s and ELMI values stabilized after 2,000 runs, with no major deviations between 3,000-7,000 iterations.

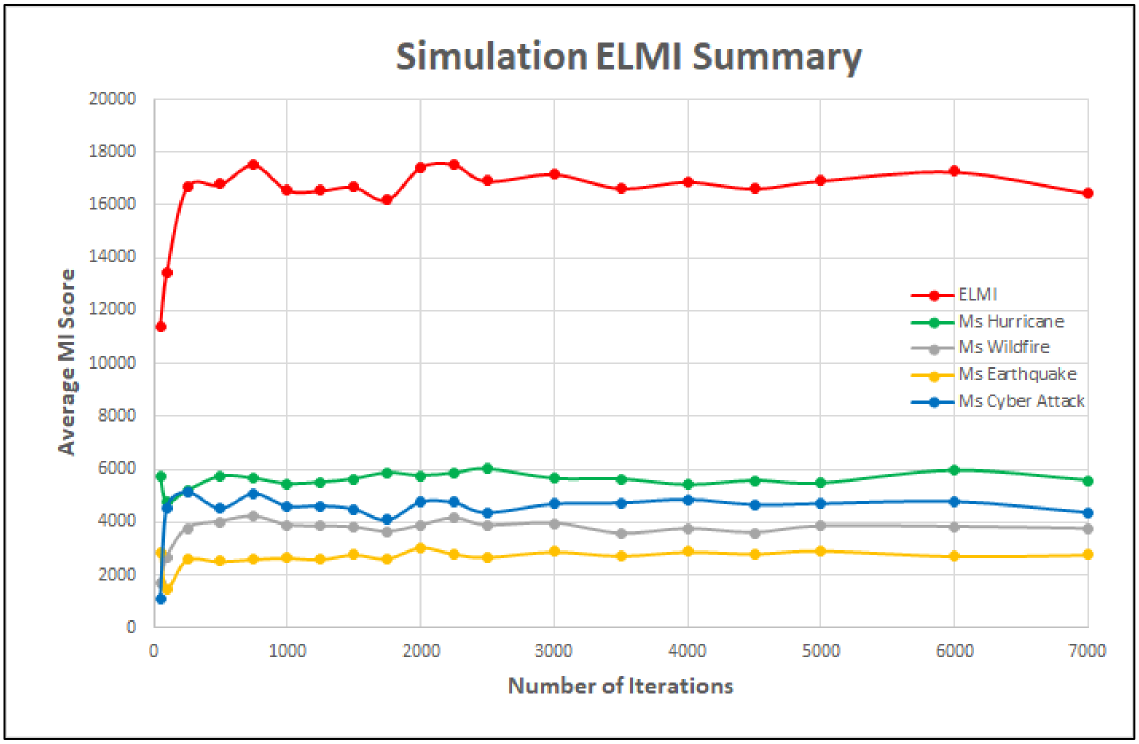


Figure 23. ELMI Summary versus Number of Iterations

Figure 23 allows the user to compare the results of different iterations runs. The team ran a statistical analysis to establish the recommended number of runs at a 95% confidence interval (CI), Table 11.

Table 11. Mission Impact Iteration Runs at 95% CI

# of iterations	500	1000	1500	2000	4000	6000
Hurricane						
Mean MI	6018.0	5362.1	5317.3	5433.5	5530.0	5950.3
+/-	992.8	655.6	531.7	470.2	330.5	280.6
% of +/-	16.50	12.23	10.00	8.65	5.98	4.72
Widfire						
Mean MI	3649.6	3699.3	3868.3	3639.7	3786.8	3817.9
+/-	779.9	563.4	466.9	394.5	286.3	235.0
% of +/-	21.37	15.23	12.07	10.84	7.56	6.16
Earthquake						
Mean MI	3320.60	3699.30	3008.33	2904.70	2667.08	2718.00
+/-	772.63	563.38	420.84	352.96	243.22	243.22
% of +/-	23.27	15.23	13.99	12.15	9.12	8.95
Cyberattack						
Mean MI	3893.60	3699.30	4534.67	4421.10	4659.45	4780.38
+/-	773.76	563.38	498.86	425.74	311.01	255.71
% of +/-	19.87	15.23	11.00	9.63	6.67	5.35
ELMI						
	16881.8	16460.0	16728.7	16398.9	16643.3	17266.6

Table 11 displays the 95% confidence intervals for iterations between 500–6,000 for the four disruptive events. MSET has 95% confidence that the MI for a wildfire event at 500 iterations will fall within 21.37% of the mean MI. At 2,000 iterations, the team is 95% confident that the MI range will fall within 6.16% of the mean MI. The MSET tool allows the user the flexibility to select several iterations. More iterations meant a greater accuracy as seen in Table 11; however, it came at a cost of extended run times. For example, the MSET tool took approximately 20 minutes to complete 50 iterations while it took about 4 hours to execute 5,000 iterations.

Figure 24 shows the comparison between percentage of error, the runtime in hour/ minute/seconds, and the number of iterations. Overall, as the number of iterations increased, the accuracy (percentage of error) increased, at the cost of longer runtime.

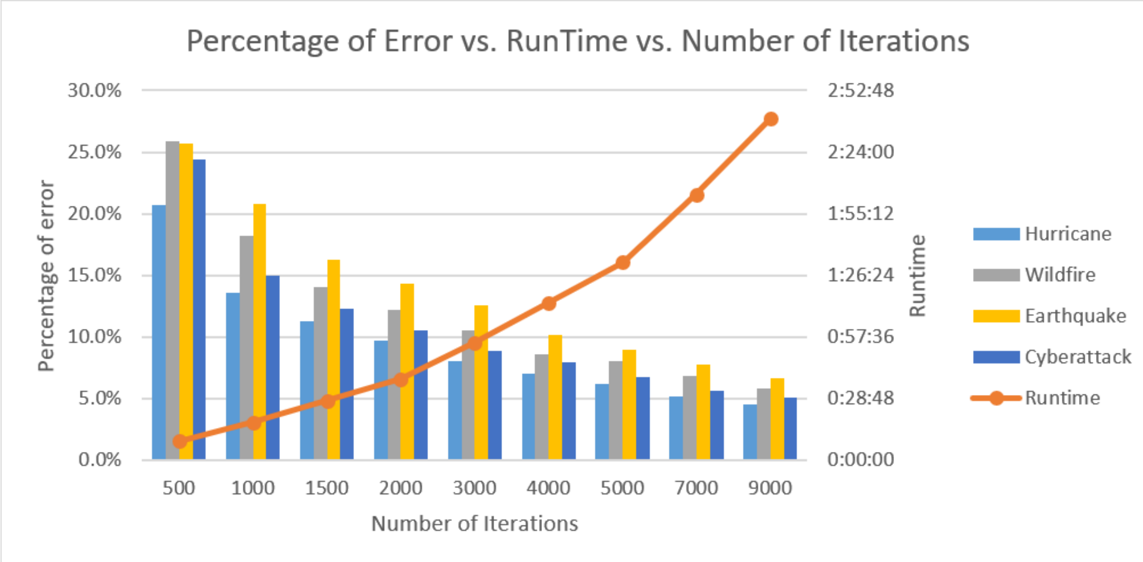


Figure 24. Comparison of Percent Error versus Runtime versus Number of Iterations for Each Disruptive Event

In Figure 24, MSET assessed that 3,000 iterations were the most ideal iteration number, with MSET being 95% confident that the M_s had stabilized within 10 to 15 percent of the true mean during a runtime of 1 hour. A single iteration option can be chosen for simple NPV calculations. If the user is looking for NPV cost comparisons, a single run is sufficient. The NPV is not calculated in the stochastic model, so the NPV is independent from the number of iterations.

Test cases were generated to verify the accurate integration of the NPV cost model, in "Cost Model (NPV)" and "ELMI" tabs. Table 12 covers the test cases used to identify successful test criteria for Spiral 4.

Table 12. Spiral 4 Test Cases for ELMI and NPV

Purpose	PV Rating (MW)	BESS Rating (MW)	DG Rating (MW)	Expected Results	Notes
Does the ELMI decrease when PV rating increase?	0.05 → 0.2	0.1	0.05	ELMI Decreases	Correct Output
Does the ELMI decrease when BESS rating increase?	0.05	0.1 → 0.2	0.05	ELMI Decreases	Correct Output
Does the ELMI decrease when DG rating increase?	0.05	0.1	0.05 → 0.2	ELMI Decreases	Correct Output
Does the cost increase when the PV Rating increases?	0.05 → 0.25	0.1	0.05	Cost NPV increases	Correct Output
Does the cost increase when the BESS Rating increases?	0.05	0.1 → 0.35	0.05	Cost NPV increases	Correct Output
Does the cost increase when the DG Rating increases?	0.05	0.1	0.05 → 0.25	Cost NPV increases	Correct Output

The resilience of a microgrid system is expected to improve (ELMI decrease) as the system DER components increase in size. The test cases were designed to examine ELMI behavior in relation to rating changes to DG, PV, and BESS. Only one DER was examined for changes to resilience behavior per test case to ensure a clear relationship correlation. The relationship between DER rating and cost was also tested to ensure expected correlation. Costs increased as the DER power rating increased. Each of these test cases matched the expected outcome trends and provided MSET the confidence to proceed to the fifth spiral.

E. FIFTH SPIRAL

MSET presented the fourth spiral of the tool to numerous stakeholders from NSETTI, including energy manager personnel from NAS Sigonella and NS Rota. Using their input, MSET identified and addressed minor integration discrepancies and condensed the feedback to form a "Trade-off Analysis" tab to assist users in DER combination comparisons. The tool cleanup phase resulted in a surprising number of discoveries which were identified late and are addressed in the last section of this chapter.

1. Trade-off Analysis Development

A major stakeholder critique was that the tool was not able to provide meaningful comparison information to the user. Each DER setup needed to be created and run separately and the outputs manually compiled for comparison. Spiral 4 of the MSET tool provided analysis results and charts for a single set of DER ratings. With the recommended 3,000 iteration run, the Monte Carlo simulation in Excel for each DER combination had a runtime of up to 2 hours. Once the simulation was complete, the user had to manually copy the simulation outputs to a separate sheet and then begin the process over again providing a different DER rating combination. After completion of the desired combinations, the user would then manually generate a graph from all the collected outputs to compare the resilience and cost results across the desired DER combinations.

To aid the base energy manager in the decision-making process, MSET automated and condensed the time-consuming manual process to simplify the calculation and display of the relationship between various DER rating combinations, resilience, and cost. The MSET tool's "Trade-off Analysis" tab allowed the user to choose three different DER rating combinations for a single disruptive event. Although the ELMI score takes into consideration four disruptive events from the resilience model, MSET reduced the scale of the calculation to consider a single disruptive event. MSET's rationale for this decision was twofold. Firstly, each disruptive event is fairly unique for each base. For example, in California, the most common disruptive events are wildfire and earthquakes; a user would assess microgrid resilience for the most likely event for their base location. Secondly, the lengthy runtime required for Excel to calculate an ELMI score was excessive, an MI score for a single disruptive event has a much shorter run time.

Three DER combination sets were created for a hurricane scenario at 2,000 iterations, see Table 13, to test the "Trade-off Analysis" tab functionality.

Table 13. Trade-off Initial Test Values

	DER Power Rating (MW)		
	PV	BESS	DG
Combination 1	0.1	0.1	0.1
Combination 2	0.1	0.1	0.2
Combination 3	0.1	0.1	0.4

The "Trade-Off Analysis" tab automatically generated data tables and column charts to display the resilience differences (both MI and Resilience score) between DER rating combinations at different maintenance levels upon completion of the simulations, see Figure 25 for graphs using the Mission Impact as the resilience metric.

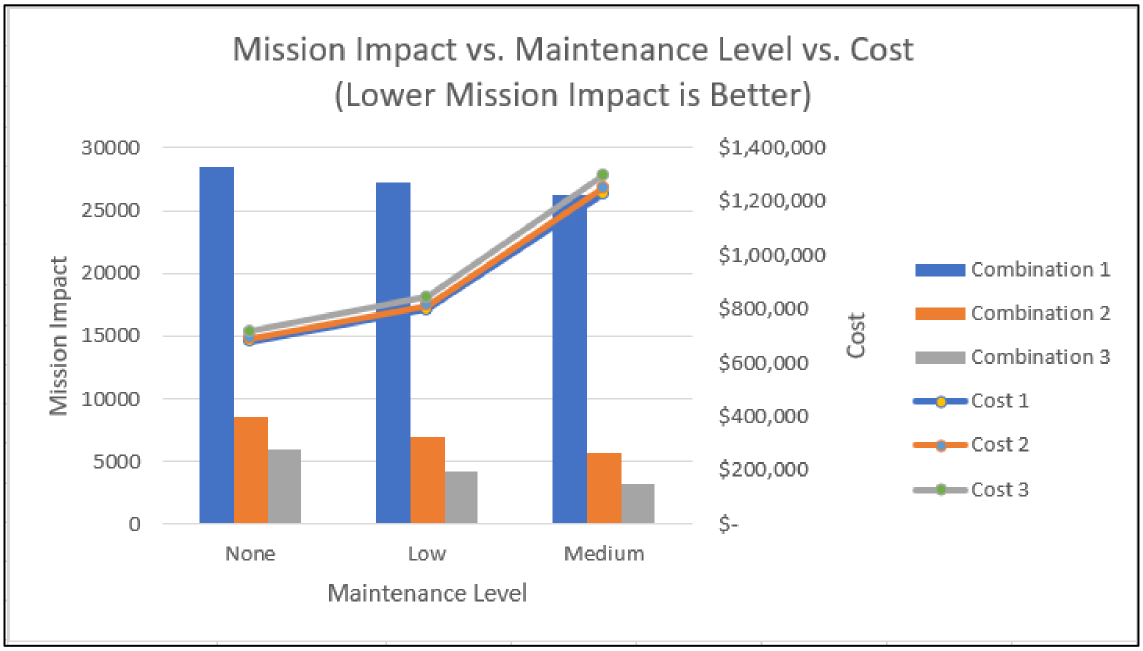


Figure 25. Mission Impact versus Maintenance versus Cost

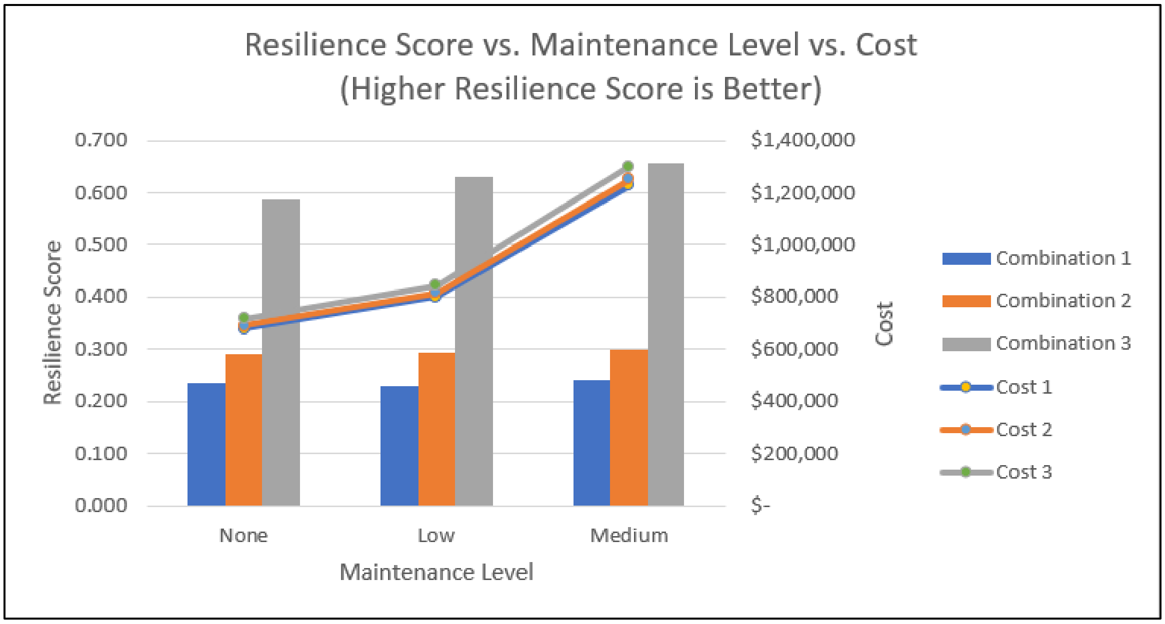


Figure 26. Resilience Score versus Maintenance Level versus Cost

The graphs in Figures 25 and 26 also feature cost comparisons of the DER combinations on the right y-axis. Each line represents the NPV of a DER combination as calculated by the "Cost Model (NPV)" tab. The cost differences among the combinations are so close because the generator cost tables are rough in granularity—at the DER scaling entered, there was no significant increase in cost between the provided generator sizes. The resilience score and MI were both displayed so the team could ensure resilience metric correlations between two different models and matched the team's expectations. As expected, the results matched: as the DG power rating rose, MI decreased, the resilience score increased, and costs increased. The MSET tool successfully performed individual testing for each spiral and thus proceeded to the final verification and validation testing for the whole MSET tool.

2. Verification and Validation

Final verification and validation testing were deemed a necessary final step for the MSET tool despite extensive testing between each integration to ensure the integrity and functionality of the final tool build. In order to verify the MSET model as a whole, test cases were conducted and analyzed to ensure results continued to correlate with expectations and the originating model results. To keep this report publicly releasable, data from a naval station air terminal was modified and randomized to avoid any For Official Use Only (FOUO) concerns. The team continued to use the Air Terminal Microgrid Design Preliminary Report as initial test values that the results of testing were compared against. The report outlined the most preferred power rating combination of DG, PV, and BESS for Rota. MSET took these preferred power ratings as the nominal configuration for the final verification and validation, as seen in the first column of Table 14.

The nominal case was expanded into three test cases to further examine how resilience changed in light of differing maintenance levels, through the "User Interface" tab. MSET ran a Monte Carlo simulation against the nominal case with maintenance levels of none, low, and medium expecting results to indicate a clear correlation between the increase of maintenance level and an improvement in resilience. The ELMI resilience metric was calculated using output results from the Monte Carlo simulation in the Resilience model, where a subjective mission impact score is multiplied by the number of hours the load was unmet. Table 14 shows the calculated resilience results.

Table 14. Nominal Test Cases

Nominal Case			
DER Rating (PV/ BESS/ DG)	**Maintenance Level**	**ELMI**	**Resilience Score**
0.3 / 0.8 / 0.32	None	13349.2	0.6468
0.3 / 0.8 / 0.32	Low	11279.6	0.6610
0.3 / 0.8 / 0.32	Medium	7854.2	0.6937

Table 14 illustrates that when the maintenance levels were increased, it resulted in a decrease in ELMI and an increase in resilience score indicating an overall improved microgrid resilience. When the maintenance level switched from none to low, the resilience score increased by 2.1% percent and ELMI was reduced by 15.5%. When the maintenance level increased from low to medium, the resilience score increased by 3.3%, and ELMI decreased by 30.4 %. Lastly, when the maintenance level is changed from none to medium, the resilience score increased by 4.7% and ELMI was reduced by 41.2%. Table 14 results illustrated a strong correlation between maintenance level and resilience and an inverse correlation between ELMI and both maintenance level and resilience.

MSET constructed a set of test cases that examined relationships between DER rating, resilience metric, and cost in the "Trade-off Analysis" tab which proved the expected correlations. To cover the permutations of DER ratings, MSET created seven test cases by doubling and halving the nominal DER ratings. Table 15 highlights the DER modifications with PV changes in yellow, BESS in green, and DG in blue.

Table 15. Trade-off Test Cases

Test Case	PV (MW)	BESS (MW)	DG (MW)
Nominal	0.3	0.8	0.32
PV	0.6	0.8	0.32
	0.15	0.8	0.32
BESS	0.3	1.6	0.32
	0.3	0.4	0.32
DG	0.3	0.8	0.64
	0.3	0.8	0.18

Each of the DER variations were run on the Trade-Off tab for a hurricane event at 5,000 iterations for all of the maintenance levels. The team intended to use this table of test cases to confirm the MSET tool functionality and determine which DER asset had the greatest impact on microgrid resilience. However, the MSET model outputs did not match expectations. The graphs shown in Figures 27 and 28 are the results from the half DG and double DG power ratings runs.

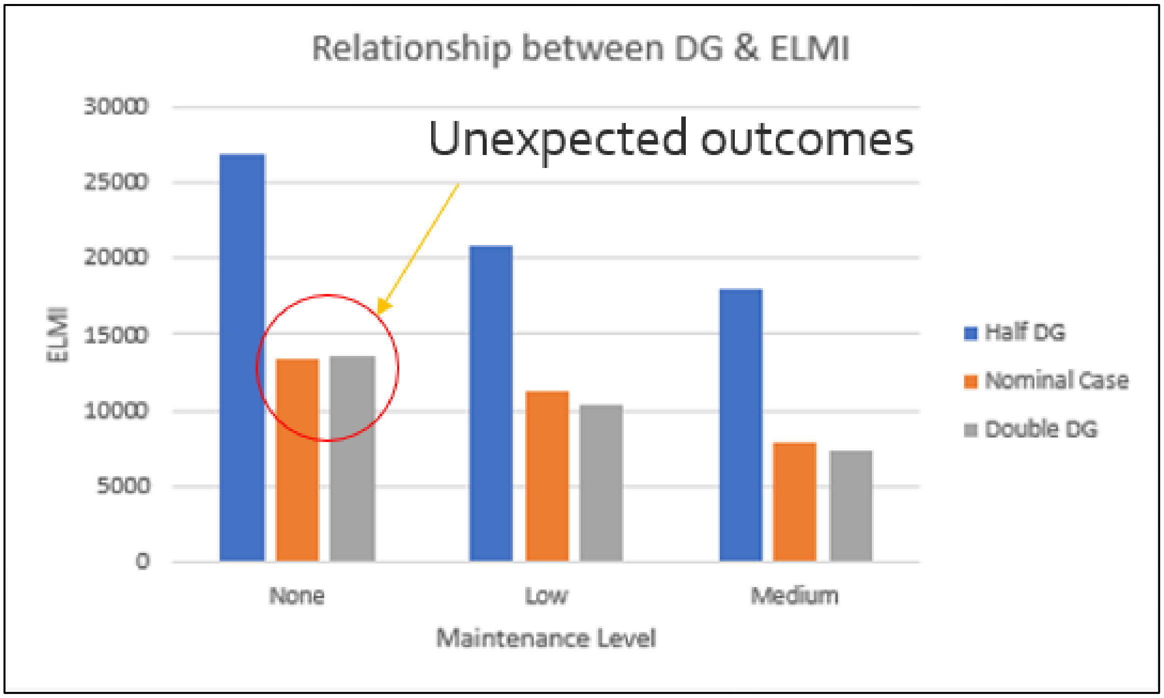


Figure 27. Unexpected Outcomes of ELMI

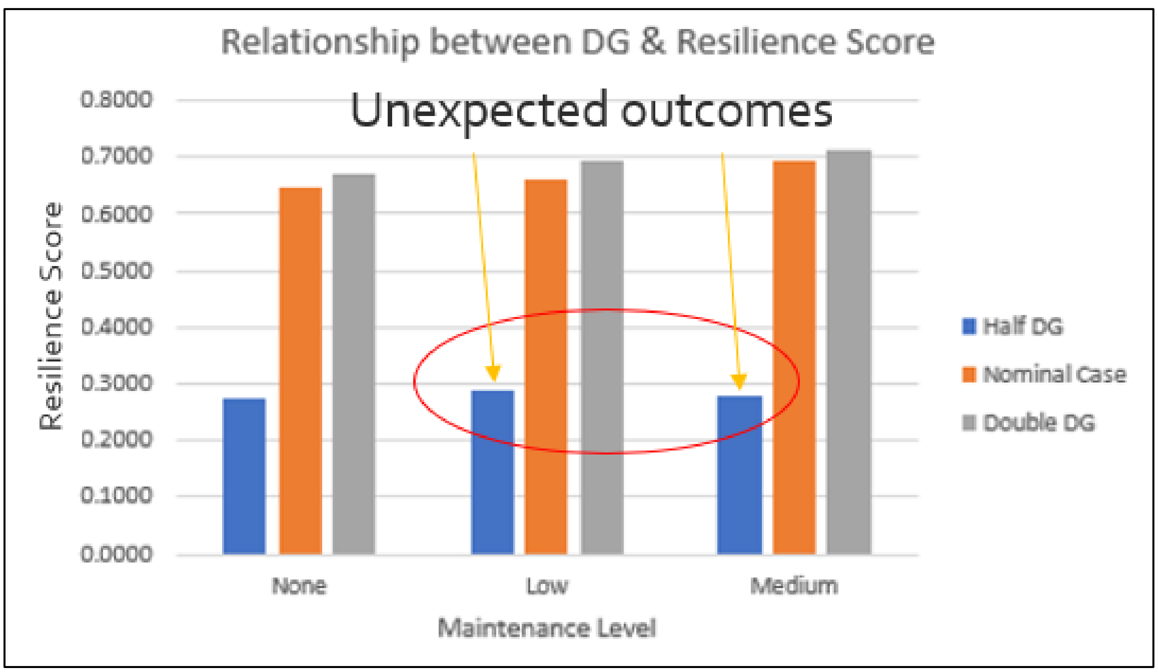


Figure 28. Unexpected Outcomes of Resilience Score

Resilience improved as expected due to the increase in DG size from half to nominal, as seen in Figure 27. However, there was very little improvement, sometimes even a reduction in microgrid resilience was observed when the DG capacity was increased from nominal to double, as seen in Figure 27 and Figure 28. These output results were concerning, as they seemed to indicate something wrong with the resilience model. Further investigation with the original tool developer and SMEs suggested that the test cases' DER ratings were oversized for the load demand, and the number of iterations were too low. The data set generated for the MSET demo had an average demand load of 138KW, with a maximum load of 238KW for the month of December. The microgrid DER rating combinations were resized to be closer in scale to the load, see Table 16.

Table 16. Test Cases with Various DER Ratings

Test Case	PV (MW)	BESS (MW)	DG (MW)
Nominal	0.1	0.1	0.1
PV	0.2	0.1	0.1
	0.4	0.1	0.1
BESS	0.1	0.2	0.1
	0.1	0.4	0.1
DG	0.1	0.1	0.2
	0.1	0.1	0.4

The number of iterations was increased to 8,000 at the suggestion of Anderson to account for the exponential distribution of the Mean Time to Repair (MTTR) utilized in the resilience score calculation. Once the suggestions were incorporated, the team attempted the two qualitative test cases shown in Table 17. The results of these test cases indicated that there was still an underlying issue with the resilience score calculation.

Table 17. Test Cases Proving Resilience Calculation Issues for PV and BESS

Purpose	DG Rating	PV Rating	BESS Rating	Expected Results	Notes
Does the resilience go up as the PV power ratings go up?	No Change	Increase	No change	Resilience score increase	Incorrect Output
Does the resilience go up as the BESS power ratings go up?	No Change	No Change	Increase	Resilience score increase	Incorrect Output

Inconsistencies were noted as the power ratings were increased separately for each DER. Based on the literature review, the expectation was that whenever there was an increase in DER power rating, the microgrid's resilience would increase. After running Monte Carlo simulations for each DER power rating, only changes in the DG's power rating matched expectations. Test cases that increased the power ratings for PV or BESS resulted in a lower resilience score, which was opposite from what was expected. As shown in Figure 30, PV rating increases resulted in a decrease in resilience score for almost all combinations, which was inconsistent with how the system should behave. The PV rating, however, increased using the MI resilience metric, seen in Figure 29, and continued to behave as expected.

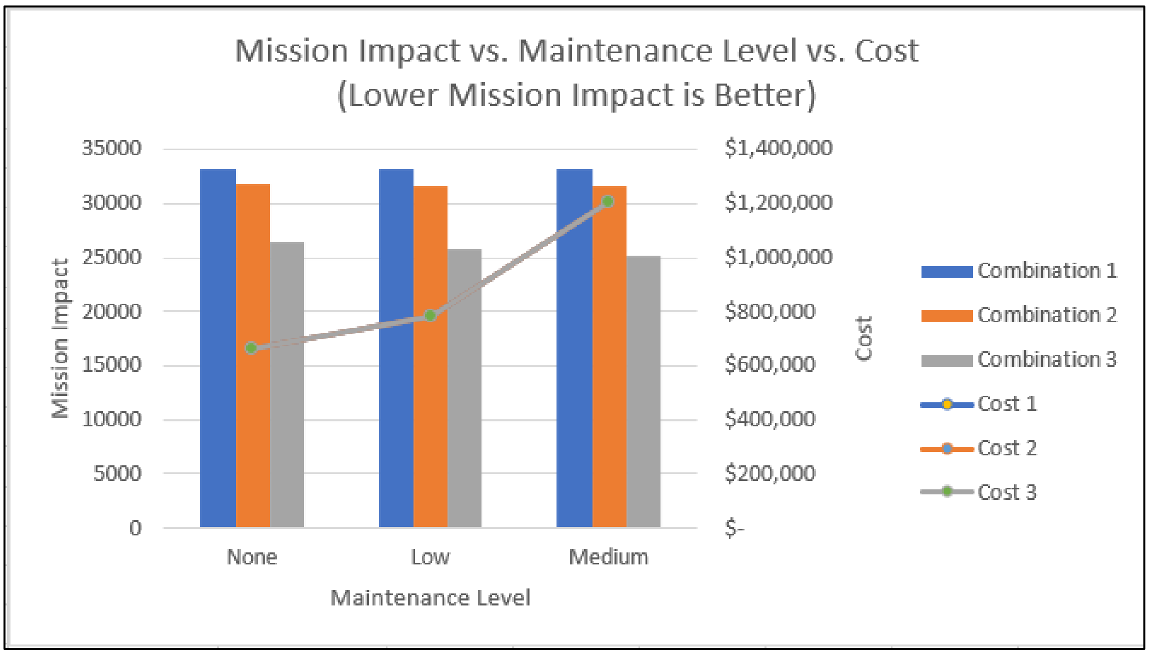


Figure 29. PV Mission Impact Distribution

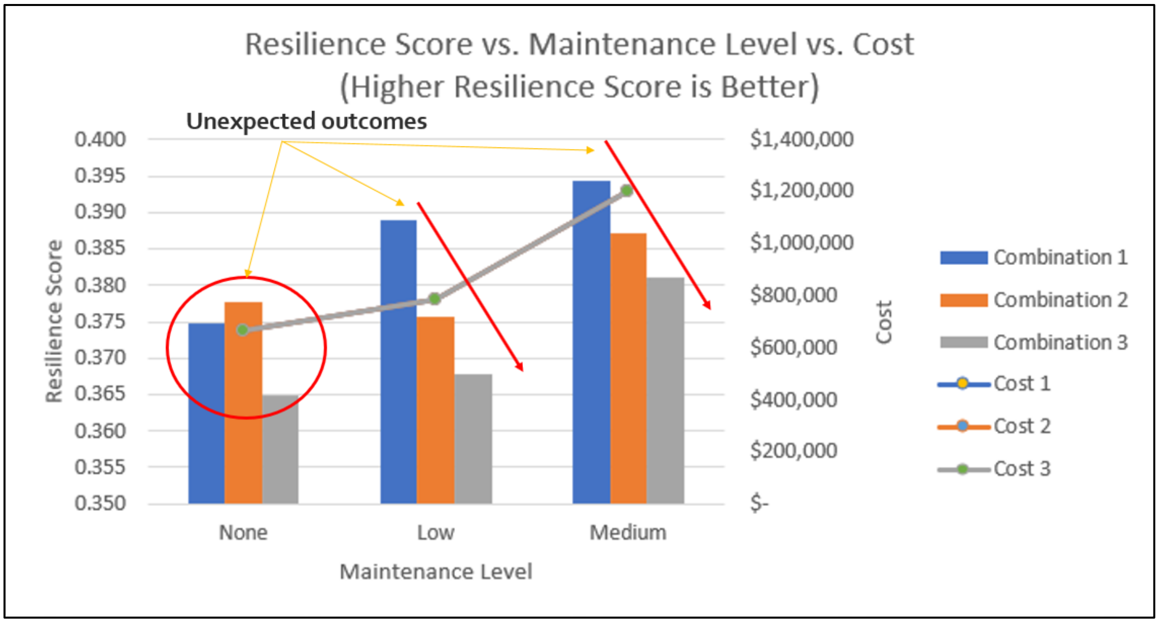


Figure 30. PV Resilience Score Inconsistencies

In Figure 30, apart from Combinations 1 and 2 at no maintenance, every increase in PV rating resulted in a decrease in resilience score. Despite incorporating suggestions from the original Resilience tool developer, these results continued to indicate an issue with the resilience score. Additional discussions and testing prompted adjustments with inconclusive results. Due to fears of inducing unexpected errors, the final decision was to leave the resilience score functionality in place for future improvement, but to remove the graphical display of the resilience score to avoid confusing the users with inconsistencies. This was applied to both the "Trade-off Analysis" tab, but also to the "User Interface" tab.

During discussions with the Resilience Model developer, it was also determined that in order to see proper resilience trending, the input DER ratings had to be limited for the resilience calculation to function properly. Anderson recommended that the sum of the DG, PV, and BESS power ratings be 1.5 times the average load for the month being analyzed. Although not ideal, limiting the DER sizes to lower ratings still allowed users to observe important trends and relationships between DER rating, maintenance level, resilience, and cost. However, it means that the DER ratings determined suitable on the "User Interface" tab cannot be used on the "Trade-Off Analysis" tab as the team originally hoped. This limitation was applied for test cases shown in Table 18 with the resilience score graph removed.

Table 18. Spiral 5 Test Cases

Purpose	Maintenance Level	PV Rating (MW)	DG Rating (MW)	Expected Results	Notes
Does the cost increase when the maintenance level increases?	None → Medium	N/A	N/A	Cost NPV increases	Correct Output
Does the trade-off analysis graph reflect the decrease in mission impact when the maintenance level and DER rating increases?	Low → Medium	0.1 → 0.15	0.15 → 0.2	The bars in the graph should decrease	Correct Output

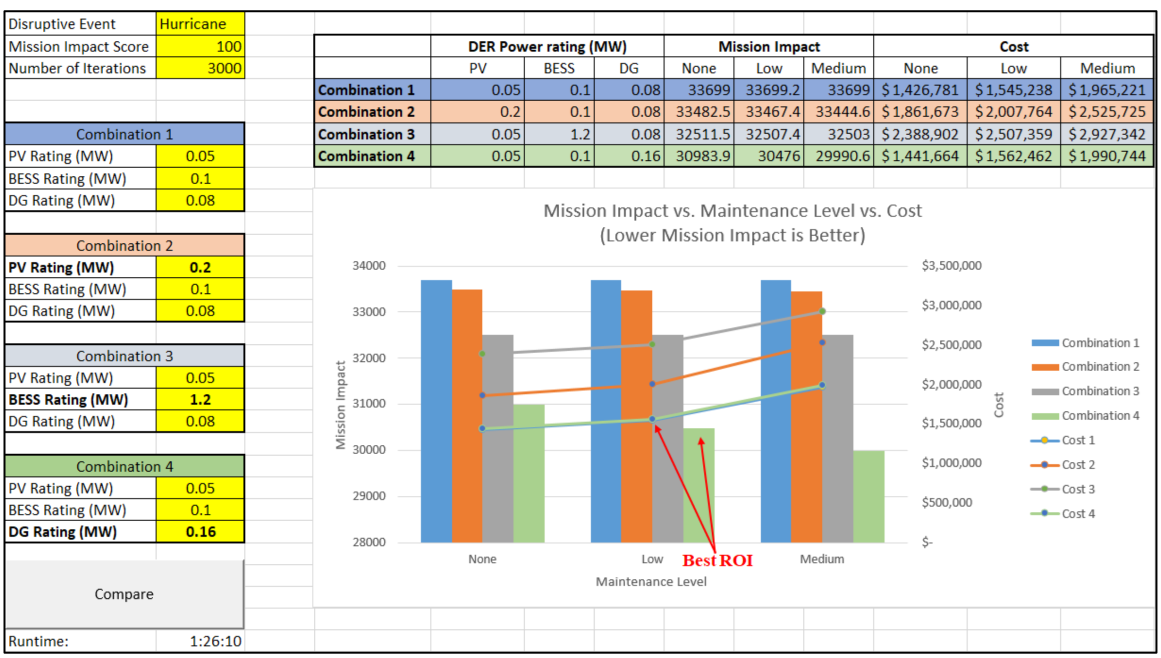
For the first test case in Table 18, the tool was checked to determine if the costs increased with an increase to the maintenance level. The tool displayed the correct results; the cost NPV increased as more maintenance was performed. During the second test case, the maintenance level and DER rating were increased, and the mission impact decreased (improved resilience), as expected. The team was careful to test these scenarios with the other DERs and not just the DGs as the DGs tended to show falsely correct responses across both resilience metrics. All of the test cases outlined in Table 12, 14, and 15 were re-run to ensure that removing the resilience outputs did not affect mission impact results. All final MI test results were compared to the initial MI test results to ensure that the excision the of resilience score did not have an effect on the MI resilience metric results. The team concluded the tool integration was complete.

3. Overall Cleanup

Cleanup of the MSET tool was initially focused was on the "User Interface" tab and improvements to the end-user output displays. Insights from potential users were taken into consideration and the NPV and MI for each maintenance level were displayed on the "User Interface" tab for additional reference. The user has the ability to select a single iteration and generate accurate costs for the microgrid for each maintenance level. If more accurate ELMI data is desired, the user can select a greater number of iterations.

The “Data” tab was reorganized for easier understanding. Data tables used to run the models that are either default or user modifiable are housed in this tab. The solar irradiance table was removed from the “Power Flow” tab and inserted into the “Data” tab, providing a single location for all user modifiable inputs.

During the development of the case study, the team realized that results were easier to illustrate by adding a fourth DER combination. The intent of the trade-off analysis was to observe changes in resilience and cost when individual DER ratings were modified. By allowing four combinations, users can establish a baseline configuration as Combination 1 to be compared against the other three combinations. The first combination is manually populated by the user with DER ratings that are approximately 50% greater than the average load for the month. Utilizing combination 1 as a baseline, the following three combinations illustrate the resilience and cost metric changes associated with increases or decreases in individual DER ratings. The new “Trade-off Analysis” tab layout is shown in Figure 31.



Disruptive Event	Hurricane
Mission Impact Score	100
Number of Iterations	3000
Combination 1	
PV Rating (MW)	0.05
BESS Rating (MW)	0.1
DG Rating (MW)	0.08
Combination 2	
PV Rating (MW)	**0.2**
BESS Rating (MW)	0.1
DG Rating (MW)	0.08
Combination 3	
PV Rating (MW)	0.05
BESS Rating (MW)	**1.2**
DG Rating (MW)	0.08
Combination 4	
PV Rating (MW)	0.05
BESS Rating (MW)	0.1
DG Rating (MW)	**0.16**
Compare	
Runtime:	1:26:10

	DER Power rating (MW)			Mission Impact			Cost		
	PV	BESS	DG	None	Low	Medium	None	Low	Medium
Combination 1	0.05	0.1	0.08	33699	33699.2	33699	$1,426,781	$1,545,238	$1,965,221
Combination 2	0.2	0.1	0.08	33482.5	33467.4	33444.6	$1,861,673	$2,007,764	$2,525,725
Combination 3	0.05	1.2	0.08	32511.5	32507.4	32503	$2,388,902	$2,507,359	$2,927,342
Combination 4	0.05	0.1	0.16	30983.9	30476	29990.6	$1,441,664	$1,562,462	$1,990,744

Figure 31. Four Combination Final “Trade-off Analysis” Tab

In the example shown in Figure 31, increasing the DG size and keeping the maintenance level at “Low” provides the best return on investment. If funding is of no concern, increasing DG size at a medium maintenance level results in the greatest resilience improvement. The cost of Combination 4 is almost identical to the cost of Combination 1 (lowest cost) and has the better resilience metrics.

The final MSET cleanup incorporated the removal of the limit lie show in Figure 20, this was replaced with the microgrid capacity line show in Figure 32. The microgrid capacity line was added to allow the user to see if the DER ratings entered will be able to support the critical load.

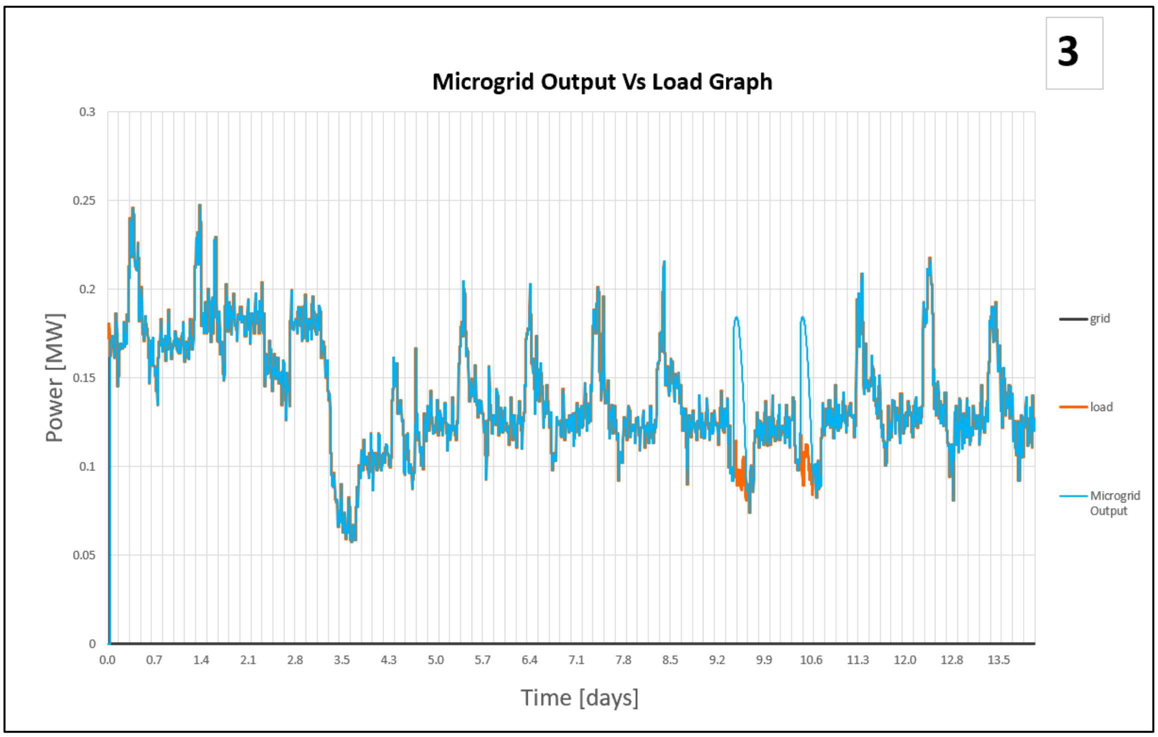


Figure 32. Microgrid Capacity Line

If the microgrid output shown in blue is above or matched with the load line shown in orange, this indicates that the microgrid is able to support the load. Figure 32 shows a sample of microgrid that is unable to support the load in areas where the orange exceeds the blue capacity line.

4. Development Summary

Development of the MSET tool was deemed complete after five spirals. The team chose the power flow model as a starting point because it was the least complex of the available models and would provide a solid foundation for further integration. The user input sheet facilitated the user experience by consolidating all necessary inputs and highlighted outputs according to the user's interests. The resilience and cost models were complex enough that MSET incorporated the entirety of each tool to avoid inducing unknown errors. Integration focused on the simplified core of each of the models by unlinking or manually zeroizing unused functions while leaving the full capability of the original models intact for possible future expansion.

V. CONCLUSIONS, FUTURE WORK, AND RECOMMENDATIONS

Chapter V presents conclusions, future work, and recommendations. A tool demonstration will be presented in a separate case study analyzing an actual naval instillation microgrid. A User Guide will accompany the MSET tool to aid users in their own analysis of a microgrid.

A. CONCLUSION

The MSET tool provides base energy managers a single integrated system design methodology to evaluate microgrid energy needs and potential trade-offs using Microsoft Excel. The team established a scope, CONOPS, and a detailed stakeholder analysis followed by research and literature reviews of relevant microgrid work exploring near peer research from EE, resilience, and cost analysis standpoints using available commercial and government sources focusing on, electrical architecture, resilience, and cost.

MSET utilized the ICSM process for the development of the tool. The ICSM process framework provided the necessary flexibility for the successful development of the MSET project. By focusing on incremental commitment and accountability, the process allowed the team to focus on accumulation of understanding throughout development, then incorporating the lessons learned and decisions made to the next spiral, each of which fully incorporated a major functional addition to the tool. The process led MSET to create five separate functional prototypes that satisfied the operational concept and stakeholders

The MSET tool began development with the power flow model to assess if the microgrid configuration was able to meet the load requirements. The integration of a user input sheet facilitated the user experience by consolidating all necessary inputs and the highlights of the model outputs according to the stakeholder interests. Once the integration was complete and tested MSET turned to the more complex resilience model. The first attempt at integrating Anderson's resilience model by removing extraneous features was met with failure. Instead, MSET integrated the entirety of the resilience model into the tool to reduce the risk of introducing errors. Integrating the entire tool leaves room for incorporation of unused features for future growth. Once the resilience model was integrated, MSET turned to Anderson's cost model; at the time, the cost model was the only available model that would add new capability to the MSET tool. The cost model integration was low risk because it was already incorporated with the resilience model. By the time the integration of Anderson's cost model was complete and tested, Hildebrand had completed his NPV cost model. MSET decided to incorporate the NPV cost model because it provided a different cost perspective in terms more familiar for the base energy managers. During the integration, the discovery was made that the resilience score produced by the resilience model was not compatible with the NPV cost model. To remedy the problem, Peterson's ELMI calculation was incorporated, using data from the resilience model. Finally, MSET developed a novel trade-off analysis method between DER ratings, microgrid costs, and resilience. The trade-off analysis portion of the tool provides valuable trend data to aid the user in making decisions that impact the base's ability to better accomplish its mission in compliance with the SECDEF energy security intent. Each prototype was an extension of the previous iteration, building on prior work based on evidence-based risk and opportunities discovered during the development cycle of the previous iterations.

The MSET tool provides a preliminary evaluation analysis but is entirely dependent on user interpretation of the requirements and constraints of the installation. The tool is useful to provide generalized recommendations based off observed trends. The purpose of the integrated tool is to provide the end user the ability to determine the correct sizing and DER distribution to support load demand based on user requirements and restrictions to meet each user's specific circumstance. Throughout the development, testing of the tool, and case study, DGs appeared to provide the best return on investment while having the greatest positive impact on resilience.

MSET successfully created a functional tool that integrated existing EE and SE microgrid analysis models. The MSET tool provides base energy managers the ability to assess a microgrid, observe the effects of changing power ratings, and compare the trade-offs between cost and resilience. This tool is a functional prototype that will serve as a solid foundation for future development and expansion for microgrid analysis needs.

B. FUTURE WORK AND RECOMMENDATIONS

Throughout the development of this tool, MSET observed gaps that could provide important value to the user if further investigated and developed. Due to a combination of time constraints and project scope, the team was unable to address these gaps, but took note of them for future investigation. The following sections outline potential avenues for future investigation in the improvement of the microgrid analysis tool.

1. Resilience Score Anomaly

During the verification and validation (V&V) of the fifth spiral, MSET identified occasional anomalous results for the resilience score. The resilience score analysis graphs in the “Trade-off Analysis” tab indicated that the overall resilience of the microgrid was decreasing as the power rating for the BESS and PV increased, which is in direct conflict with the MI resilience graphs. The unexpected results were discussed in detail in Chapter IV.E.2 of this technical report. MSET determined that the most logical path forward to meet schedule deadlines was to remove the resilience score from the “Trade-off Analysis” tab and rely exclusively on the MI resilience data.

2. Capability to Change Microgrid Architecture

Adding the ability to select or change the microgrid architecture, such as adding more PV, DG, or ESS in the initial setup, would improve the capabilities of the tool and enable it to more accurately represent the microgrid being considered. The MSET tool only considers a single microgrid architecture consisting of a single PV, DG, and BESS, which allows for the user to change the energy rating of the DERs and compare the MI of differing rating configurations after a particular disturbance occurs. Utilizing a single architecture simplifies the initial analysis of the microgrid by allowing the user to observe the changes in cost and resilience per type of DER. In addition to changing the architecture options, the team also recommends adding the ability to add different DER sources, such as wind turbines and nuclear energy sources. The addition of different DER sources can better aid base energy managers in considering microgrid options.

3. Runtime Efficiency

Runtime issues were encountered during V&V testing due to the Monte Carlo simulation. As the number of iterations increased, Excel processing inefficiencies drove the runtimes into multiple hours, tying up computers and making testing a longer process than anticipated. It may be possible to make improvements to VBA code to improve efficiency; however, adding further complexity may require a move to a more powerful programming language such as Python to resolve issues with time efficiency.

4. DER Ratings

The MSET tool's trade-off analysis is limited to DER ratings that meet 1.5 times the average load. If the DER ratings are much higher than 50% of the average load for the selected month, the output data is not accurate and cannot be used to infer resilience trends. The DERs are so large compared to the load that the resilience calculation no longer matters. Comparing changes to DER ratings no longer holds any value because the system is already oversized and thus sufficiently resilient. Since the trade-off analysis only works when DER ratings are 50% greater than the average load, the necessary baseline DER ratings rarely meet peak load demands. This issue could potentially be solved with the addition of load profile and shedding capabilities in the tool, which would in turn allow for the tool to simulate a microgrid that changes its output based on the demand, however further investigation is warranted.

5. Load Profiles and Load Shedding

An advantageous expansion is to investigate is the ability to break the single load profile into its constituent parts for finer granularity. The team expects that breaking the load profile into criticality categories (mission impact range or building type), would allow for a more comprehensive tool. The ability to apply an MI score to the categorized loads will provide a more accurate assessment of resilience. Additionally, once the data is broken down into mission impact categories, the tool would have the ability to scale specific loads by criticality priority. The load shedding investigation will have to take into account if the increased fidelity provides enough value to explore in depth.

Load shedding is an important energy management feature as it identifies and prioritizes critical and non-critical loads. Load shedding implementation is only applicable to the tool once the tool has developed features for multiple architectures and multiple load profiles; however, load shedding could be an interesting avenue to explore in terms of how an energy manger may approach the design of a microgrid, as well as how the changes in load demand may affect resilience. The introduction of load shedding would expand opportunities for users to explore more complex combinations of architecture and loads, but it will be difficult to balance the user interface complexity to ensure it does not overwhelm the intended users.

6. Energy Management Strategy

Further exploration of the energy management strategy used across the MSET tool is recommended. The models MSET used for integration already had embedded energy management strategies that could not be modified without adverse effects on the tool. However, differences between the tools internal and unique energy management strategies may cause inherent disconnects between individual tool outputs. Due to inconsistencies, the “Resilience” and “Trade-off Analysis” tabs are not directly correlated with the “Power Flow” model. An effort should be made to determine the individual energy management strategies employed by each model and bring the strategies into alignment with each other to increase the interoperability of the MSET tool.

7. Varying Confidence Intervals

Interviews with stakeholders suggested that the base energy managers may desire a different confidence interval than 95% used in the MSET tool. Providing the flexibility to adjust the confidence interval will allow the stakeholders to implement a confidence interval that is more applicable to the respective situation and should be a fairly simple addition.

8. Comparing Multiple Disturbances for Mission Impact

In earlier iterations, the MSET tool executed and analyzed different disturbances (fire, earthquake, hurricane, and cyber-attack) and compared the four mission impact scores in one execution. Executing the tool for multiple disturbances consequently caused the run time to increase significantly. To reduce the run times, the tool was reduced to executing and observing one disturbance at a time. Translating the MSET tool to a more powerful programming language could enable this capability without compromising efficient run times. Future iterations of the tool may provide the capability to run all the applicable disturbances to the microgrid and execute them in one run for an ELMI in the trade-off analysis

9. Location-Based Simulation

The ability to automate the PV characteristics database such that an end user could input their location to update the PV table for the selected geographic area would greatly enhance the usability of the tool. The MSET tool's power flow model calculates PV ratings based on the month selected. In the current setup, the PV output data is locked to Spain. The MSET team found out while writing the user guide that the solar irradiance data used to generate the PV sine wave in the power flow model is not as easily adjusted for different geographic areas as was initially thought. It was not possible to correct this issue, because the discovery was found in the late stages of the project. A discussion with the developer of the PV sine wave in the power flow model brought to light that a significant amount of trial and error went into the development of the initial PV curve. This does not translate into a clean-cut procedure for future end users. MSET has identified two possible paths forward: manually adjust the PV curve for each new geographic area or plot the PV output data from NREL or the Photovoltaic Geographical Information System instead of using the sine wave calculation.

SUPPLEMENTALS

The following section explains the four supplemental materials available in conjunction with this work. Those interested in obtaining the first two public release supplementals can use the link available with the main thesis's catalog entry in the NPS Institutional Archive Calhoun. To access the remaining two restricted supplementals, please contact the NPS library.

Supplemental 1 (User Guide):

This user guide is meant to explain the microgrid analysis tool (MSET tool) and provides detailed usage instructions. The guide establishes detailed explanations for the tabs, specific cells, functions, and provides clarification on interpretation as well as standard operating procedures. This is a public release document.

Supplemental 2 (MSET Tool):

This supplemental is the Distribution A version of the MSET Tool in an Excel Format.

Supplemental 3:

This supplemental is a case study for the methodology and the usage of the MSET tool. This is a restricted documented. For those interested in obtaining the supplemental document for review, please contact the NPS Dudley Knox Library.

Supplemental 4:

This supplemental is the MSET Excel file that is associated with the case study. This is a restricted documented. For those interested in obtaining the supplemental document for review, please contact the NPS Dudley Knox Library.

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